ENERGY AND THE CONSERVATION LAW

Paul Peirce Stief

Physics: A Human Endeavour

Unit 3 ENERGY AND THE CONSERVATION LAWS

Text

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"... I believe, basically, we have not been cautious enough of the meaning of science in our generation, to teach it in a way which would be understood and appreciated and felt by the students. We have very little of the positive values of science outside of the applications which are obvious to anybody living in this age. In other words, my claim is, and this is something we should discuss, that we have not been teaching our science in a humanistic way. We have been teaching science at every level, in a certain sense, as a certain bag of tricks which the bright boy or girl could learn and show off with, or at least get a great deal of pleasure out of—the same kind of pleasure, but not quite as sharp, as he would get out of plane geometry.

Now, science is a very different thing . . . it is an adventure of the whole human race to learn to live in and perhaps to love the universe in which they are. To be a part of it is to understand, to understand oneself, to begin to feel that there is a capacity within man far beyond what he felt he had, of an infinite extension of human possibilities—not just on the material side (whatever that may mean, because the more we study the material side, the more and more it recedes) . . .

So what I propose as a suggestion for you is that science be taught at whatever level, from the lowest to the highest, in the humanistic way. By which I mean, it should be taught with a certain historical understanding, with a certain philosophical understanding, with a social understanding and a human understanding in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations."

From the address of I. I. Rabi at AAAS meeting of Educational Policies Commission, 27 December 1966, Washington, D.C.

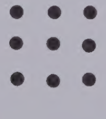
Preface

Physics: A Human Endeavour is an examination of some parts of man's attempt to understand the physical world. We call physics a "human endeavour" because the development of our understanding of the physical environment is the result of interactions between human minds and nature.

It is perhaps most important in the world of today, a world in which there is an "information explosion", to seek a broad understanding of the ways in which information is obtained, and the limitations, applications, and implications of such knowledge.

In order to achieve this understanding, we shall not only examine the physics of the twentieth century, but we shall study the evolution of scientific thought from the past to our contemporary point of view.

This examination can reveal to us one characteristic of the human mind that is particularly interesting. It is symbolized by the nine dots we have used as the basis for the simple puzzle stated below.



Draw the nine dots on a piece of paper.

Join all nine dots by four straight lines without lifting your pencil from the page.

Try it!

If you have not succeeded yet, the answer is found on the back cover.

It is fun to watch a group of people attempt this problem. Invariably, people draw lines in all directions, but stop when they reach the outside row of dots. They seem hemmed in by those outside dots as if they feel them representing some kind of boundary on the problem. In order to succeed, your pencil must break through this self-imposed boundary. (There was nothing in the instructions to suggest such a boundary existed!) You may know other puzzles of this kind, or remember problems that you have solved only after breaking through some such boundary on your thinking. We shall call such mental boundaries *paradigms*. Most people, faced with a problem, search for some familiar pattern or model on which to base their thinking. That is, consciously or unconsciously, they seek to establish a paradigm. We suggest that by examining some of the major paradigms that have existed in the past, and the ways in which they were broken, we can go a long way towards recognizing the paradigms of today, an important ability for success in the discipline of physics, or any other human endeavour. As the distinguished Canadian critic, Northrop Frye, has said "It is a part of the whole educational process to recognize as far as possible the extent of one's own conditioning and to try to go as far as humanly possible in becoming aware of what one's own assumptions and axioms are." (Northrop Frye in an

interview with Bruce Mickleburgh in "Monday Morning", September, 1972.)

Now let us make some specific comments on the structure of the course.

There are six units in all. Each has one or two central themes, and makes its own kind of contribution to your knowledge of physics.

Much of what happens in the universe involves *motion*, and it is important to be able to describe how and why objects move. These topics, called kinematics and dynamics, form the basis of the information in Unit 1.

Unit 2 is a further discussion of the laws of motion. We expand upon the concepts of simple motion by taking the laws out of the limited sphere of the earth's gravity and applying them to the motions of our solar system and ultimately, the universe. As you will see the analogy to the dot problem applies. Man had to expand beyond the earth (the limits of the dots) into the universe (beyond the dots) in order to continue his search for knowledge. Where is man located in the vastness of space? Where are the stars? Is there an order to the universe? The variety of answers to these questions, and the knowledge that the answers are still changing, is the concern of Unit 2. The development of man's sources of useful energy and the possibility of a twentieth century energy crisis are also considered.

In the third unit the formulation of a few of the famous "Conservation Laws" is discussed with emphasis on the fascinating properties of momentum, energy, and the transformation of waves.

Unit 4 concentrates on the use of "models" in science, particularly focussing on the classic conflict between two rather successful models to describe the nature of light—the particle model proposed by Sir Isaac Newton, and the wave model championed by the Dutch physicist Christian Huygens. Although we shall see how this particular conflict was resolved, we shall also see how a similar problem about the nature of light still exists today.

The story of electricity, the relationship between electricity and magnetism, and the tremendous impact that developments in this field of physics have had on our way of life are traced in the fifth unit.

Finally, the world of the very small, the world of objects of atomic and nuclear sizes, the world of x-rays, gamma rays, and radioactive particles, the world of nuclear fission, fusion, and atomic energy, is probed in Unit 6.

Throughout the text, you will find questions at the end of most sections. These are usually straightforward questions which can be answered directly from the preceding material. They focus on the major points made in the section. Problems, graded into A and B levels of difficulty, are provided at the end of each chapter to help you develop further your ability and insight into the issues in the text.

Many of the questions at the end of the sections and chapters are marked with an asterisk. These are questions of a discussion type and so the "answers" will not be found at the back of the book.

We believe that no student taking this course should limit his reading to this text alone. One of the habits a student must acquire is to pursue a given topic from several points of view. To this end, there are many references made throughout the text to books that have been read and enjoyed by other students studying physics at your level.

Finally, we should like to point out to you the importance of laboratory work. Ultimately, all science is guided by the phrase "theory guides, but experiment decides". Measuring properties of nature directly usually raises a host of difficulties that are not met when working through the same material with pencil and pad. Some whimsical scientists (original sources unknown by the authors) have given concise expression to the feelings that any student of science can share from time to time in the forms of "*Murphy's Law*"—If anything can go wrong it will—and "*Allen's Axiom*"—When all else fails, read the instructions. We hope that you don't find these applicable to yourself too often this year, but when you do, smile, reorganize, and try again!

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Prologue

It is not surprising that, after his death in 1727, Newton was practically deified, especially in England, by poems such as this one:

Newton the unparallel'd, whose
Name
No Time will wear out of the Book
of Fame,
Celestial Science has promoted more,
Than all the Sages that have shone
before.
Nature compell'd his piercing Mind
obeys,
And gladly shows him all her secret
Ways;
Gainst Mathematics she has no
defence,
And yields t'experimental
Consequence;
His tow'ring Genius, from its certain
Cause
Ev'ry Appearance a priori draws
And shews th'Almight Architect's
unalter'd Laws.

(From J. T. Desagulier, *The Newtonian System of the World, the Best Model of Government,* an Allegorical Poem.)

The triumph of Isaac Newton in uniting motion and astronomy is one of the glories of the human mind, a turning point in the development of science and man. Never before had a scientific theory been so successful in predicting the future, and never before had the possibilities for future development in science seemed so unlimited.

Newton's work not only led others to new heights of accomplishment in science, but profoundly altered man's view of the universe. Physicists after Newton explained the motion of planets around the sun by treating the solar system as a huge machine. Although the parts of the solar system are held together by gravitational forces rather than by nuts and bolts, the motion of these parts relative to each other, according to Newton's theory, is still fixed forever once the system has been put together.

We call this model of the solar system the *Newtonian world-machine.* It is a theoretical system, not a real one, because the mathematical equations which govern its motions take account of only a few of the properties of the real solar system and leave out others. In particular, the equations take no account of the structure and chemical composition of the planets, or the heat, light, electricity, and magnetism which are involved. The Newtonian system takes account only of the masses, positions, and velocities of the parts of the system, and the gravitational forces among them.

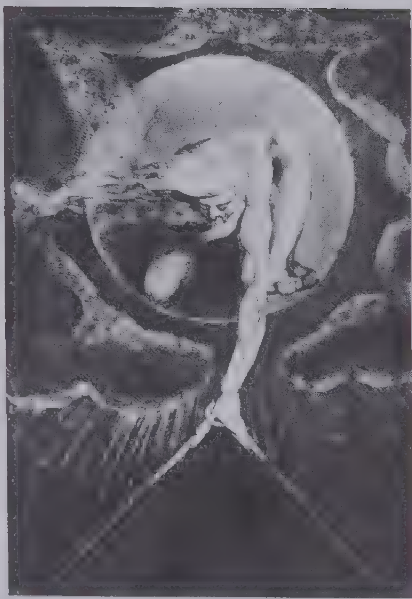
The idea of a world machine does not derive entirely from Newton. In his Principles of Philosophy, René Descartes, the most influential French philosopher of the seventeenth century, clearly stated the idea that the world is like a machine. He wrote:

> I do not recognize any difference between the machines that artisans make and the different bodies that nature alone composes, unless it be that the effects of the machines depend only upon the adjustment of certain tubes or springs, or other instruments, that, having necessarily some proportion with the hands of those who make them, are always so large that their shapes and motions can be seen, while the tubes and springs that cause the effects of natural bodies are ordinarily too small to be perceived by our senses. And it is certain that all the laws of Mechanics belong to Physics, so that all the things that are artificial, are at the same time natural.

Robert Boyle (1627-1691), a British scientist who studied the properties of air, expressed the mechanistic viewpoint even in

his religious writings. He argued that a God who could design a universe that would run by itself like a machine was more wonderful, and more deserving of human worship, than a God who simply created several different kinds of matter and gave each a natural tendency to behave in the way it does. Boyle also thought it was insulting to God to believe that the world-machine would be so badly designed as to require any further divine intervention after it had once been created. He suggested than an engineer's skill in designing "an elaborate engine" is more deserving of praise if the engine never needs supervision to regulate it or keep it from getting "out of order." "Just so," he continued,

> . . . it more sets off the wisdom of God in the fabric of the universe, that he can make so vast a machine perform all those many things which he designed it should, by the meer contrivance of brute matter managed by certain laws local motion and upheld by his ordinary and general concourse, than if he employed from time to time as intelligent overseer, such as nature is fancied to be, to regulate, assist, and control the motions of the parts.



According to Boyle and many other scientists in the seventeenth and eighteenth centuries, God was the first and greatest theoretical physicist. God, they said, set down the laws of matter and motion; human scientists can best glorify the works of God by discovering and proclaiming these laws.

Our main concern in this unit is with physics after Newton. In mechanics the Newtonian theory was developed to accommodate a wider range of concepts. Conservation laws became increasingly important. These powerful principles offered a new way of thinking about Newtonian mechanics, and so were important in the application of Newton's theory to other areas of physics.

Newton's mechanics treat directly only a small range of experiences, those concerning the motion of simple bodies. Will the same theory work when applied to phenomena on earth as well as to those in the heavens? Are solids, liquids, and gases really just machines, or mechanical systems, which can be explained by using the same ideas about matter and motion which Newton used in explaining the solar system?

At first sight, it might seem unlikely that everything can be reduced to matter and motion, because we feel, hear, smell, and see many things that seem different from matter and motion. What about colours, sounds, odours, hardness and softness, temperature and so forth? Newton himself believed that the mechanical view would be useful in investigating these other properties. In the preface to the *Principia* he wrote:

> I wish we could drive the rest of the phenomena of Nature by the same kind of reasoning from mechanical principles, for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are mutually impelled towards one another, and cohere in regular figures, or are repelled and recede from one another. These forces being unknown, philosophers have hitherto attempted the search of Nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of Philosophy.

Knowing the laws of motion, scientists after Newton strove to apply them in many different areas. We shall see in this unit how the fundamental laws of Newton were used to form the basis of a new and enlarged understanding of the physical world.

Chapter 10 *Momentum*

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Momentum

Chapter Ten

10.1 Conservation of Mass

If the universe is to go on forever, then the "stuff" of which it is made cannot disappear. The suggestion that the total amount of material in the universe does not change is really an old idea. The Roman poet Lucretius (first century B.C.) restated a belief held in Greece as early as the fifth century B.C.:

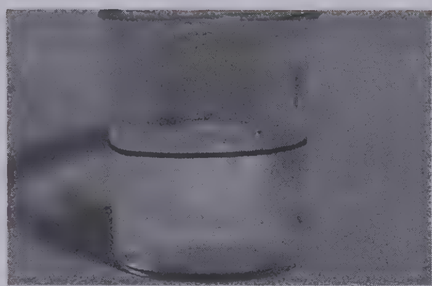
> . . . and no force can change the sum of things; for there is nothing outside, either into which any kind of matter can emerge out of the universe or out of which a new supply can arise and burst into the universe and change all the nature of things and alter their motions. (*On the Nature of Things*)

Just twenty-two years before Newton's birth, the English philosopher Francis Bacon included the following among his basic principles of modern science:

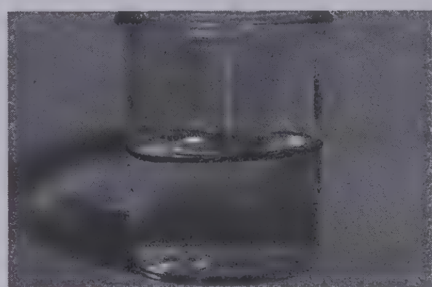
> There is nothing more true in nature than the twin propositions that "nothing is produced from nothing" and "nothing is reduced to nothing" . . . the sum total of matter remains unchanged, without increase or diminution. (*Novum Organon* 1620, ii, 40)

These quotations illustrate the belief that the amount of physical matter that makes up the universe remains the same—no new matter appears and no old matter disappears. While the form in which matter exists may change, matter in all our ordinary experience appears to be somehow indestructible; if we break a large boulder into dust and pebbles, we do not change the amount of stone in the universe.

To test the belief that the quantity of matter remains constant, we need to know how to measure that quantity. Scientists recognized several centuries ago that it should not be measured by its volume. For example, if we put water in a container, mark the water level, and then freeze the water, we find that the volume of the ice is larger than the volume of the water we started with. This is true even if we are careful to seal the container so that no water can possibly come in from the outside. Similarly when we compress gas in a closed container, the volume of the gas decreases, even though none of the gas escapes from the container.



Ice



Water

See Activity 10.1, *Conservation of Mass.*

A nail . . . A nail exposed to the elements

Following Newton, we have come to regard the mass of an object as the appropriate measure of the amount of matter it contains. In our use of Newtonian theory we have been assuming that the mass of an object does not change. But what if we burn the object to ashes or dissolve it in acid? Does its mass remain unchanged even in such chemical reactions?

A burnt match has a smaller mass than an unburnt one; an iron nail as it rusts increases in mass. Has the mass of these things really changed? Or does something escape from the match, and is something added to the iron of the nail, that will account for the changes in mass? In the eighteenth century there was a strong belief that any changes of mass in chemical reactions could be accounted for by assuming that there is something that escapes or something that enters from outside. Not until the end of the eighteenth century, however, was a sound experimental basis for this belief provided by Antoine Lavoisier (1743-1794).

Lavoisier caused chemical reactions to occur in closed flasks and carefully weighed the flasks and their contents before and after the reaction. For example, he showed that when iron was burned in a closed flask, the mass of the iron oxide produced was equal to the sum of the masses of the iron and the oxygen used in the reaction. With experimental evidence like this at hand he was able to announce with confidence:

> We may lay it down as an incontestable axiom that in all the operations of art and nature, nothing is created; an equal quantity of matter exists both before and after the experiment . . . and nothing takes place beyond changes and modifications in the combinations of these elements. Upon this principle the whole art of performing chemical experiments depends. (*Traité Elementaire de chimie, 1789*)

Lavoisier was convinced that if he put some material in a well-sealed bottle and measured its mass, then he could return at any later time and find the same mass regardless of what happened to the material inside the bottle during the interval. Despite changes from solid to liquid or liquid to gas, etc., despite changes of colour or consistency, despite even violent chemical reactions of the material inside the bottle, at least one thing would remain unchanged—the mass of the matter in the bottle.

In the years after Lavoisier's pioneering work, a vast number of similar experiments were performed with ever increasing accuracy and always with the same result. As far as can be measured with sensitive balances (having an accuracy of better than 0.000001%), mass is conserved in chemical reactions, even when light and heat are allowed to enter or leave the system. Despite changes in location, shape, chemical composition and so forth, **the mass of any closed system remains constant.** This is the statement of what we shall call the **law of conservation of mass.**

Conservation of mass was demonstrated in experiments on chemical reactions in closed flasks. Precision, equal-arm balances were used by Lavoisier and other chemists of the time.

Q1 If 50 cm^3 of alcohol are mixed with 50 cm^3 of water, the mixture amounts to only 98 cm^3. Is this a contradiction of the law of conservation of mass?

Q2 It is estimated that every year at least 9×10^6 kg of meteroric dust falls onto the earth. The dust is mostly debris that was moving in orbits around the sun.

a) Is the earth a closed system as regards the law of conservation of mass?

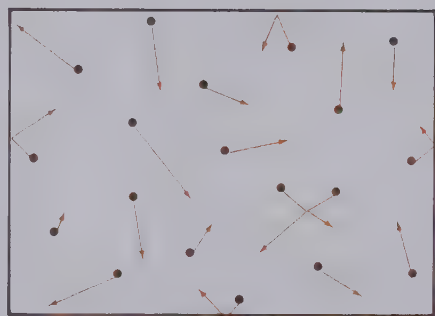
b) How large would the system including the earth have to be in order to be considered very, very nearly closed?
c) The mass of the earth is about 6×10^{24} kg. Do you want to reconsider your answer to part (a)?

10.2 The Search for a "Quantity of Motion"

Newton's law of motion and gravitation unite terrestrial and celestial physics and explain the causes of motion. One cannot look at objects moving in the real world for long, however, before they collide with something else. Collisions of various sorts occur whenever two objects interact. The clapping of hands or bouncing of a ball are obviously collisions. But there are many less obvious interactions that are collisions. Molecules that constitute the air are continually colliding with each other and with the walls of a container they may be in. Collisions of large moving objects with these molecules provide the force we call *air friction.* Rubbing your hands together involves friction caused by "collision" interactions between the molecules in each hand. Atoms and their nuclei are often studied by being bombarded with tiny high speed particles. By studying the results of these collisions, much can be learned about the composition and structure of matter.

When observing collisions we notice that bodies slow down and eventually stop moving as a result of their interactions. It would appear that the amount of motion in the universe is decreasing through the collisions and that the universe, like any other machine, is slowing down. To many seventeenth century philosophers, the idea of a universe that was running down was incompatible with the idea of the perfection of God. Surely He would not construct such an imperfect mechanism. The feeling grew that some aspect of motion remained unchanged or constant throughout these interactions. René Descartes wrote in his *Principles of Philosophy* (1644):

> It is wholly rational to assume that God, since in the creation of matter He imparted different motions to its parts, and preserves all matter in the same way and conditions in which He created it, so He similarly preserves in it the same quantity of motion.

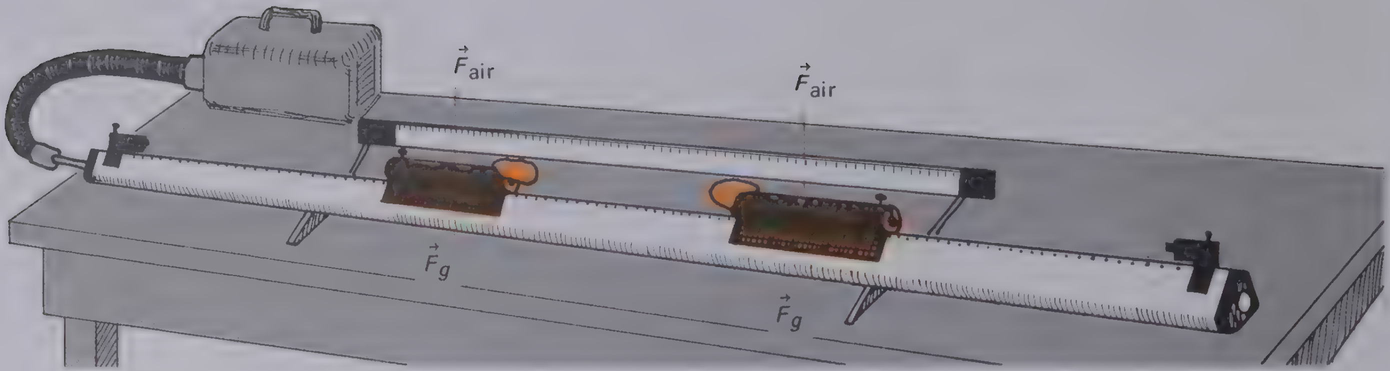


Atoms of molecules of gases collide with each other and with the walls of containers.

The problem was to discover a way to measure a "*quantity of motion*" which remains unchanged in an interaction. At first, this search may look futile. When you drop a book, it comes to rest on the earth. The motion apparently disappears. When two cars collide, they soon come to rest. Billiard balls may rebound off each other a few times, but then come to a halt. In each case, motion has apparently disappeared.

As we have seen before, we can often learn how nature is really behaving if we try to study some simple system. The simplest system to consider would be a collision involving only two bodies, free from any net forces acting on them from outside the system. We could very nearly achieve this by using gliders on a perfectly level, frictionless air track. Consider the forces that would act on the gliders as they move toward each other at a constant speed.

Experiments 10.1, 10.2, and 10.3, *Collisions with Carts.*



Experiment 10.4, *Collisions on an Air Track.*

The net force in the vertical direction on each glider is zero and there are practically no forces at all acting on them horizontally once they are put into motion (there is a very small force of air friction that we will ignore). When they collide, each glider experiences a horizontal force on it caused by the other body, but there is no net force acting on either body caused by anything except the other body. The two gliders form what is called an isolated system.

A system of bodies on which no net force acts from outside the system is called an isolated system.

In an isolated system, there are usually bodies lying outside the system that exert large forces on bodies inside the system. For example, the earth exerts a large gravitational pull on each glider. But this force is balanced by the molecules of the air lying between the glider and the track. Therefore, there is no *net* force acting on the gliders caused by the earth. The gliders are considered to be isolated from the earth.

Q3 Two pucks on a frictionless, horizontal surface are joined by a spring.
a) Can they be considered an isolated system?
b) How do gravitational forces exerted by the earth affect your answer?
c) What about forces exerted by the pucks on the earth?

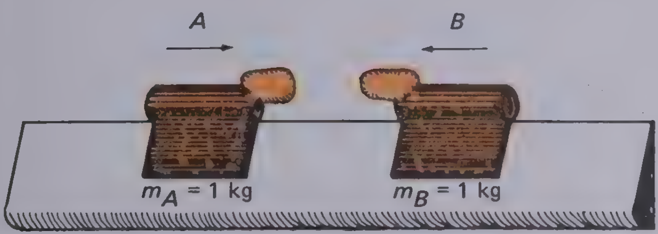
10.3 Collisions

Now let us consider the behaviour of the gliders in this isolated system to see if there is some "quantity of motion" that remains the same before and after the collision. The gliders have a lump of soft putty at each end so they will stick together on impact. But what shall we use as a measure of "quantity of motion"? Suppose we try speed. Is the total amount of speed in the isolated system the same before and after any collision? Let us look at one case in which two gliders, each of mass 1 kilogram, approach each other at the same speed of 1 metre per second.

Case 1

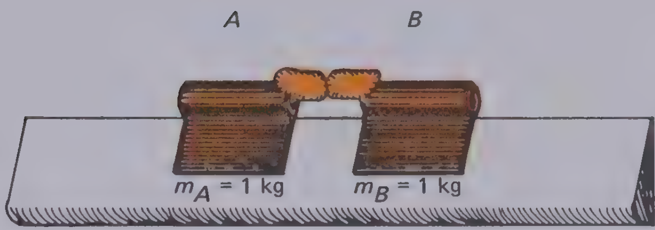
Before Collision

$v_A = 1\frac{\text{m}}{\text{s}} \quad v_B = 1\frac{\text{m}}{\text{s}}$



After Collision

Both come to rest



Sum of speeds before

$$= v_A + v_B,$$
$$= 1\frac{\text{m}}{\text{s}} + 1\frac{\text{m}}{\text{s}},$$
$$= 2\frac{\text{m}}{\text{s}}.$$

Sum of speeds after

$$= v'_A + v'_B,$$
$$= 0 + 0,$$
$$= 0.$$

We see that the speed has not been conserved.

But perhaps velocity rather than speed is a conserved quantity in Case 1. By considering velocities instead of speeds, we include the directional nature of motion, since velocity is a vector quantity and has both magnitude and direction.

Sum of velocities before

$$= \vec{v}_A + \vec{v}_B,$$
$$= \left(+ 1\frac{\text{m}}{\text{s}}\right) + \left(-1\frac{\text{m}}{\text{s}}\right),$$
$$= 0.$$

Sum of velocities after

$$= \vec{v}\,'_A + \vec{v}\,'_B,$$
$$= 0 + 0,$$
$$= 0.$$

Velocity is a conserved quantity in this case! The total velocity before the collision is equal to the total velocity after the collision.

Notice that in this collision, *other* possible ways to measure "quantity of motion" are also conserved. For example, mass × velocity.

Sum of (mass × velocity) of each object before

$$= m_A\vec{v}_A + m_B\vec{v}_B,$$
$$= \left(+ 1\ \text{kg}\frac{\text{m}}{\text{s}}\right) + \left(- 1\ \text{kg}\frac{\text{m}}{\text{s}}\right),$$
$$= 0.$$

Sum of (mass × velocity) of each object after

$$= m_A\vec{v}\,'_A + m_B\vec{v}\,'_B,$$
$$= 0 + 0,$$
$$= 0.$$

So would other combinations of mass and velocity, for instance velocity/mass or $(\text{mass})^2 \times$ velocity.

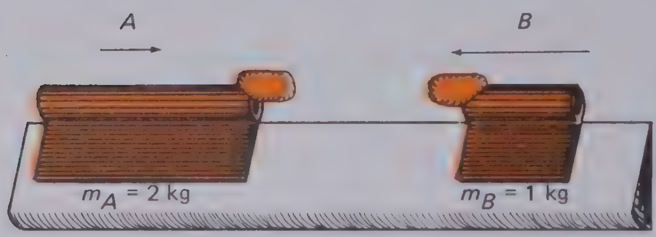
From a consideration of just this one collision, we have found several possible cases of conservation, but have been able to rule out any idea of speed conservation.

Let us examine the results of a different collision. This time, glider A has twice the mass of glider B, but B has twice the speed of A.

Case 2

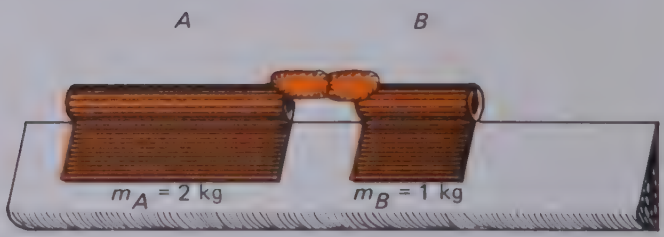
Before Collision

$\vec{v} = +1\frac{\text{m}}{\text{s}} \quad \vec{v} = -2\frac{\text{m}}{\text{s}}$



After Collision

Both come to rest



Sum of velocities before

$$= \vec{v}_A + \vec{v}_B,$$
$$= \left(+1\frac{\text{m}}{\text{s}}\right) + \left(-2\frac{\text{m}}{\text{s}}\right),$$
$$= -1\frac{\text{m}}{\text{s}}.$$

Sum of velocities after

$$= \vec{v}\,'_A + \vec{v}\,'_B,$$
$$= 0.$$

The velocity is not conserved in this case.

But let us examine (the quantity mass × velocity).

Sum of (mass × velocity) before

$$= m_A\vec{v}_A + m_B\vec{v}_B$$
$$= (2\text{ kg})\left(1\frac{\text{m}}{\text{s}}\right) + (1\text{ kg})\left(-2\frac{\text{m}}{\text{s}}\right)$$
$$= \left\{(+2) + (-2)\right\}\text{kg}\frac{\text{m}}{\text{s}},$$
$$= 0.$$

Sum of (mass × velocity) after

There is, in effect, a single mass after collision since the gliders stick together

$$= \overbrace{(m_A + m_B)}\vec{v},$$
$$= (3\text{ kg})\,(0),$$
$$= 0.$$

The product of mass × velocity is conserved.

Notice further, that other combinations of mass and velocity, such as velocity divided by mass, or mass squared times velocity are not conserved.

Of all the possibilities we have considered just one combination was conserved in both collisions. That was the product mass × velocity.

We can summarize this behaviour algebraically with the following equation:

$$\underbrace{m_A\vec{v}_A + m_B\vec{v}_B}_{\text{before collision}} = \underbrace{m_A\vec{v}\,'_A + m_B\vec{v}\,'_B}_{\text{after collision}}.$$

Q4 What special property does the "total amount of mass times velocity" display in the collisions discussed thus far?

Q5 Two carts collide head-on and stick together. In which of the following cases do you think the carts will be at rest immediately after the collision?

Cart A		Cart B	
mass (kg)	velocity before (m/s right)	mass (kg)	velocity before (m/s left)
a) 2	3	2	3
b) 2	2	3	3
c) 2	3	3	2
d) 2	3	1	6

Film Loops 10.1, 10.2, *One-Dimensional Collisions.*

10.4 Conservation of Momentum

Although we discussed just one type of isolated system in the last section, laboratory experiments and activities that are available for you to do should convince you that the *vector sum of the quantities mass times velocity always remains unchanged when bodies in an isolated system interact*. The mass times the velocity of a body is a very useful way of expressing "quantity of motion". Because it is a conserved quantity, it has been given a special name—**momentum**.

The momentum of a body is the product of its mass and velocity. It is often given the symbol $\vec{p}$.

Thus $\vec{p} = m\vec{v}$.

Momentum is a vector quantity because the product of a scalar and a vector is a vector.

The behaviour that we have discovered is called the **law of conservation of momentum** and is stated:

In any isolated system, the total momentum of the parts before an interaction is the same as their total momentum after the interaction.

For an isolated system of two bodies, we can write using symbols

Experiments 10.5 and 10.6, *Photographs of Collisions.*

$$\vec{p}_1 + \vec{p}_2 = \vec{p}\,'_1 + \vec{p}\,'_2,$$

or,

$$\vec{p}_{\text{total before}} = \vec{p}_{\text{total after}}.$$

Since there is no change in the total momentum of an isolated system, then any *gain* in momentum of one body must just equal the *loss* in momentum of the second body. We can also write the law of conservation of momentum algebraically as:

$$\Delta\vec{p}_2 = -\Delta\vec{p}_1 .$$

This can be read as: *The change in momentum of one body is equal in magnitude but opposite in direction to the change in momentum of the second body.*

Momentum was the first of several concepts that have been discovered to be conserved during interactions. Another will be discussed in the next chapter and several others are listed in the margin.

Other "Conservation Laws" include
Conservation of
- mass
- mechanical energy
- total energy
- angular momentum
- electric charge
- electron-family number
- muon-family number
- baryon-family number
- strangeness number
- isotopic spin

Conservation laws are particularly pleasing to physicists because they emphasize the underlying simplicity in the behaviour of nature. The law of conservation of momentum reveals a sense of order out of the apparent chaos of motion that surrounds us. Physicists have come to place a great trust in the conservation laws. So far, this faith has been well placed. One example of faith in the conservation laws is seen in the prediction in 1931 of the existence of a particle with no electric charge and a mass much less than that of the electron, the lightest particle known at the time. This was done in order to account for a small apparent loss in momentum during the decay of radioactive nuclei. The new particle, called a neutrino, was predicted in 1931, but not observed until 1956. The significant point is, however, that physicists accepted its existence long before 1956, based largely on their faith that the law of conservation of momentum must hold true.

Q6 Compute the momentum of
a) a 0.14-kg baseball thrown at 30 m/s toward home plate,
b) a 1000-kg rhinoceros running at his top velocity of 15 m/s east,
c) a 1500-kg automobile moving at 30 m/s north.

Q7 What would be the velocities of the following bodies if they each had a momentum of 800 kg $\frac{m}{s}$ to the right?
a) a 100-kg football player,
b) a 1600-kg automobile.

See also Problems 10.1 to 10.4 on page 16.

The law of momentum conservation is used to gain information about interactions that would be difficult or impossible to get in other ways. Let us see how by an example.

Example Problem

A pellet from a BB gun is fired into a small orange juice can packed with sand, that is mounted on an air track glider. The pellet is brought to a halt inside the can. The following information is known:

Mass of pellet $= m_p = .50$ g,

Mass of can and sand $= m_c = 100.0$ g,

Velocity of can and sand and pellet after impact $= \vec{v}' = 30.0$ cm/s.

Find the velocity of the pellet just before impact.

Solution

Let all vector quantities directed right be positive.

Let velocity of pellet before impact be $\vec{v}_p$.

Isolated system being considered—pellet, can, and sand.

$$\vec{p}_{\text{total before}} = m_p\vec{v}_p + m_c\vec{v}_c.$$

$$\vec{p}_{\text{total after}} = (m_p + m_c) \times \vec{v}.$$

But, $$\vec{p}_{\text{total before}} = \vec{p}_{\text{total after.}}$$

Therefore, $$m_p\vec{v}_p + m_c\vec{v}_c = \left(m_p + m_c\right) \times \vec{v}',$$

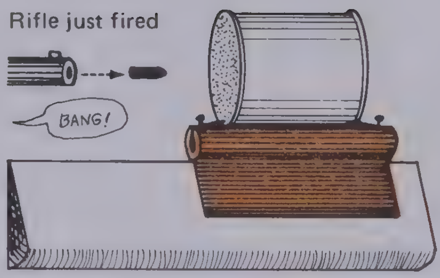
and $$(.50\text{g})\,\vec{v}_p + 0 = (100.5\text{g}) \times (+30 \text{ cm/s}).$$

$$.5\vec{v}_p(g) = +3{,}015\text{g cm/s},$$

$$\vec{v}_p = \frac{+3015\text{g cm/s},}{.5\text{g}}$$

$$= +6030 \text{ cm/s}.$$

The velocity of the pellet just before impact was 60 m/s [right].



Film Loop 10.5, *Recoil.*

Notice that we solved this problem without knowing the sizes or the kinds of forces involved between the pellet and the sand. This information would be very difficult to acquire. The law of conservation of momentum has provided a relatively simple way to study a complicated interaction. Herein lies the power of a conservation law—it yields information about the results of an event without the necessity of dealing with the event in its full complexity.

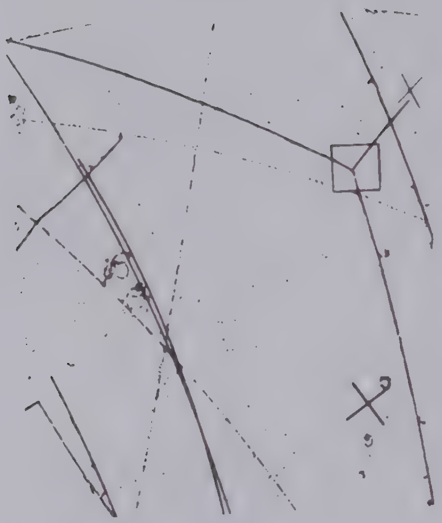


Fig. 10.2

Activity 10.2, *Momentum of Exchange.*

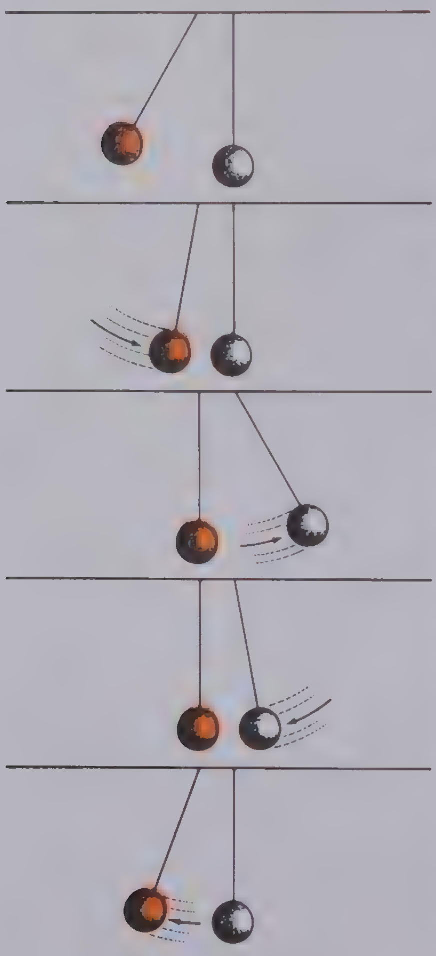
Fig. 10.2 is a picture of an event taking place in a device called a cloud chamber. A charged particle moving through the vapour in the chamber leaves a thin trail of water vapour which can be photographed. The Y-shaped track was produced when an alpha particle struck an oxygen nucleus. From the length, direction, and density of the water droplets along the paths, it is possible to compute the velocities of separation. Using the principle of conservation of momentum, then, we can get the ratio of the masses of the fragments. Scientists use this kind of information to learn more about the interactions of fundamental particles.

Q8 A .080-kg bullet is fired horizontally into a 9.0-kg block of wood which is free to move on a frictionless surface. The initial velocity of the bullet was 600 m/s. If the bullet stays imbedded in the wood, calculate the velocity of the bullet and wood after the impact.

Q9 A firecracker bursts into two fragments, one, that we shall call *A*, moves at 10 m/s, while the other, *B*, moves at 15 m/s in the opposite direction. What is the ratio of the masses of the fragments?

See also Problems 10.5 to 10.12 on page 16.

10.6 Elastic and Inelastic Collisions



In 1666, members of the recently-formed Royal Society of London witnessed a demonstration at one of the Society's regular meetings.

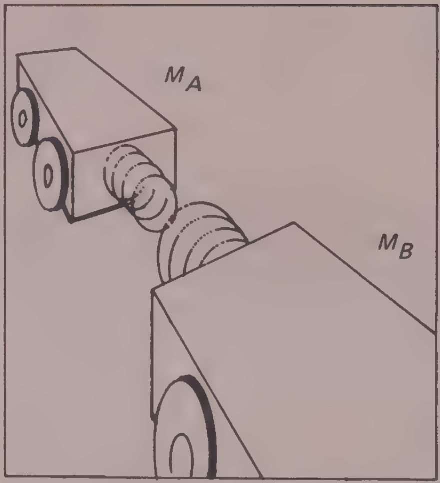
Two hardwood balls of equal size were suspended at the ends of two strings to form two pendula. When one ball was released from rest at a certain height, it swung down and struck the other, which had been hanging at rest.

After impact, the first ball was very nearly motionless and the second ball swung up to nearly the same height as that from which the first had been released. When the second ball returned and struck the first, it was now the second ball which came nearly to rest, and the first swung up to almost the same height from which it had started. And so the motion continued, back and forth through many swings.

This demonstration aroused great interest among members of the Society. In the years immediately following, it also generated heated and often confusing arguments. Why did the balls rise each time to nearly the same height? Why was the motion "transferred" from one ball to the other when they collided? Why didn't the first ball bounce back or continue moving slowly forward?

Our law of momentum conservation would not prohibit different results; it says only that the momentum of ball *A* just before it strikes *B* is equal to the total momentum of *A* and *B* just after collision; it does not say how *A* and *B* share the momentum. Ball *A* stopping and ball *B* going on at *A*'s initial velocity is just one of infinitely many different outcomes that

Deriving Newton's 3rd Law from the Conservation of Momentum



Suppose two bodies with masses m_A and m_B, placed on a horizontal frictionless surface, are squeezed against a spring that is joined to one of them and then released. The bodies would comprise an isolated system and would move apart under the force of the spring. The law of conservation of momentum would require that

$$\Delta\vec{p}_B = -\Delta\vec{p}_A.$$

This can be written as,

$$m_B\vec{v}'_B - m_B\vec{v}_B = -\left(m_A\vec{v}'_A - m_A\vec{v}_A\right)$$

or, $$m_B\left(\vec{v}'_B - \vec{v}_B\right) = -m_A\left(\vec{v}'_A - \vec{v}_A\right)$$

or, $$m_B\left(\Delta\vec{v}_B\right) = -m_A\left(\Delta\vec{v}_A\right).$$

But, from Newton's second law

$$\vec{F}_{net} = m\vec{a} = m\frac{\Delta\vec{v}}{\Delta t}$$

or, $$\vec{F}_{net}(\Delta t) = m\Delta\vec{v}.$$

Applying Newton's second law to object A and then to object B,

$$\vec{F}_{B\text{ on }A}(\Delta t) = m_A\left(\Delta\vec{v}_A\right)$$

and, $$\vec{F}_{A\text{ on }B}(\Delta t) = m_B\left(\Delta\vec{v}_B\right)$$

therefore $$\vec{F}_{A\text{ on }B}(\Delta t) = -\vec{F}_{B\text{ on }A}(\Delta t).$$

The net force exerted by B on A is the only force acting on A, and thus is equal to the net force.

But, each body acts on the other for the same time Δt,

Therefore, $$\vec{F}_{A\text{ on }B} = -\vec{F}_{B\text{ on }A},$$

which is just what Newton's third law claims.

See also Problems 10.13 to 10.20 on page 16.

would all be consistent with conservation of momentum. In Table 10.1, columns 1 and 2 show just a few of the velocities after the collisions of two balls which would satisfy the conservation of momentum when ball A strikes ball B initially at rest.

Columns 3 and 4 show the calculations confirming that momentum is conserved under *any* of these after-collision conditions.

Table 10.1

1	2	3	4	5	6
$\vec{v}'_A$	$\vec{v}'_B$	$\vec{p}$ total before	$\vec{p}$ total after	Vis Viva (before)	Vis Viva (after)
		$m_A\vec{v}_A + m_B\vec{v}_B$	$m_A\vec{v}'_A + m_B\vec{v}'_B$	$m_A{v_A}^2 + m_B{v_B}^2$	$m_B(v'_A)^2 + m_B(v'_B)^2$
0	+1	(+1) + 0 = +1	0 + (+1) +1	1 + 0 = 1	0 + 1 = 1
−1	+2	(+1) + 0 = + 1	(−1) + (+2) +1	1	1 + 2 = 3
−3	+4	(+1) + 0 = +1	(−3) + (+4) +1	1	9 + 16 = 25
−5	+6	(+1) + 0 = +1	(−5) + (+6) +1	1	25 + 36 = 61

Film Loop 10.3, *Inelastic One-Dimensional Collisions.*

In 1668 three men reported to the Royal Society on the matter of such impacts. The three men were the mathematician John Wallis, the architect and scientist Christopher Wren, and the physicist Christian Huygens. Wallis and Wren had partial answers to explain some of the features of collision; Huygens analysed the problem in complete detail.

Huygens explained the behaviour of the hardwood pendula by showing that in such collisions *another* conservation law holds, in addition to the law of conservation of momentum. Not only was the vector sum of $m\vec{v}$'s conserved, but so was the ordinary arithmetic sum of mv^2's!

Christian Huygens (1629-1695) was a Dutch physicist. He devised an improved telescope with which he discovered a satellite of Saturn and saw Saturn's rings clearly. He was the first to understand centripetal force, and he invented the pendulum-controlled clock. We shall hear more of Huygens later. Huygens' scientific contributions were major, and his reputation would undoubtedly have been even greater had he not been overshadowed by his contemporary, Newton.

Almost twenty years later, the German, Gottfried Leibniz, called the quantity mv^2, the *vis viva.* Columns 5 and 6 at the right of Table 10.1 show that the result observed at the Royal Society meeting, ball A stopping and B going on at A's initial speed, is the only result consistent with *both* the conservation of momentum and the conservation of vis viva.

By the nineteenth century, the quantity $(1/2)mv^2$ had been shown to represent a specific form of a more general concept called *energy.* This scalar quantity $1/2mv^2$ is now called *kinetic energy*. In modern algebraic form, the relationship Huygens discovered in 1668 can be expressed as

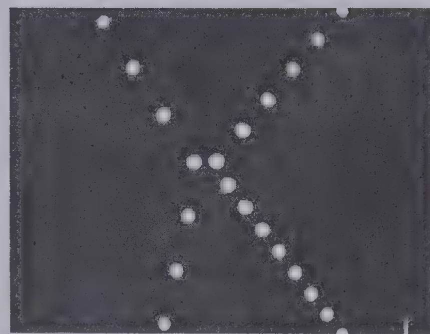
$$\tfrac{1}{2}m_A{v_A}^2 + \tfrac{1}{2}m_B{v_B}^2 = \tfrac{1}{2}m_A{v'_A}^2 + \tfrac{1}{2}m_B{v'_B}^2.$$

Huygens, and others after him for about a century, did not use the factor 1/2. The quantity mv^2 was called *vis viva*, Latin for "living force." The term vis viva is no longer in use.

The reason for the $\frac{1}{2}$, which doesn't really affect the rule at all here, will become clear in the next chapter. The equation above, then, is the mathematical expression of the conservation of kinetic energy.

When bodies collide in such a way that the total kinetic energy before the collision is the same as the total kinetic energy after the collision, we say that the collision was *perfectly elastic*. In such collisions, the colliding bodies do not crumple, smash, dent, stick together, heat up, or in some other way have their insides changed. In perfectly elastic collisions both momentum and kinetic energy are conserved.

$$\left.\begin{aligned} \vec{p}_{\text{total before}} &= \vec{p}_{\text{total after.}} \\ KE_{\text{total before}} &= KE_{\text{total after.}} \end{aligned}\right\} \text{In } \textit{perfectly elastic} \text{ collisions}$$


A highly elastic collision.

Collisions between steel ball bearings, glass marbles, hardwood balls, billiard balls, or some rubber balls (silicone rubber) are almost perfectly elastic; if the collisions are not so violent as to damage the bodies, the total kinetic energy after the collision might be typically as much as, say 96% of its value before the collision. Examples of perfectly elastic collisions are found in collisions between atoms or subatomic particles.

Is the total kinetic energy conserved in all interactions? It is easy to see that it is not. Consider the first case of section 10.2 in which two gliders of equal mass and speeds (and with putty between the bumping surfaces) approach each other, stick together, and stop.

Total kinetic energy before collision	*Total kinetic energy after collision*
$= \frac{1}{2} m_A v_A{}^2 + \frac{1}{2} m_B v_B{}^2,$	$= \frac{1}{2} m_A v_A'{}^2 + \frac{1}{2} m_B v_B'{}^2,$
$= \frac{1}{2}\,(1\ \text{kg})\left(1\frac{\text{m}}{\text{s}}\right)^2 + \frac{1}{2}\,(1\ \text{kg})\left(1\frac{\text{m}}{\text{s}}\right)^2,$	$= 0 + 0,$
$= 1\ \text{kg}\ \frac{\text{m}}{\text{s}}\ ^{2}.$	$= 0.$

Kinetic energy is not conserved in this collision, or in any collision in which the bodies stick together.

In most collisions that we witness, kinetic energy is not conserved, the sum of $\frac{1}{2}mv^2$'s after the collision is less than before the collision. Such collisions are *inelastic*. When the colliding bodies remain together and stop moving after collision, there is a complete loss of the initial kinetic energy and the collision is *completely inelastic*. In all inelastic collisions, momentum is conserved, but kinetic energy is not.

$$\left.\begin{aligned} \vec{p}_{\text{total before}} &= \vec{p}_{\text{total after.}} \\ KE_{\text{total before}} &\neq KE_{\text{total after.}} \end{aligned}\right\} \text{In } \textit{inelastic} \text{ collisions}$$


A perfectly inelastic collision.

Still, Leibniz was convinced that $\left(\frac{1}{2}\right)mv^2$ is, in some way, *always* conserved. In order to save his conservation law, he invented an ingenious explanation for the apparent loss of vis viva. He maintained that the vis viva is not lost or destroyed, but

Leibniz (1646-1716), a contemporary of Newton, was a German philosopher and diplomat, an adviser to Louis XIV of France and Peter the Great of Russia. Independently of Newton, he invented the method of mathematical analysis called calculus. A long, public dispute resulted between the two great men concerning charges of plagiarism of ideas.

merely "dissipated among the small parts" of which the colliding bodies are made. This was pure speculation and Leibniz offered no supporting evidence. Nonetheless, in Chapter 11 we shall see that this was an anticipation of the modern ideas about the connection between energy and the motion of molecules.

But Leibniz extended conservation ideas to phenomena other than collisions. For example, when a stone is thrown straight upward, its quantity of $\left(\frac{1}{2}\right) mv^2$ decreases as it rises, without any collision. At the top of the trajectory, $\left(\frac{1}{2}\right)mv^2$ is momentarily zero, and then reappears as the stone falls. With insight, Leibniz asked whether the "vis viva" given to a stone at the start is somehow stored as it rises, instead of being lost. This idea that $\left(\frac{1}{2}\right)mv^2$ is just one part of a more general, and really conserved quantity, will lead us in Chapter 11 directly to the most powerful of all laws of science—the law of conservation of energy.

Q10 i) Classify the following collisions being highly elastic, inelastic, or completely inelastic.

a) A ball is hit by a baseball bat.
b) Two cars with hard metal bumpers collide and come to rest.
c) Two cars with rubber bumpers collide at low speed and rebound.
d) An egg falls to the floor.
e) A tennis ball falls to the sidewalk and bounces.
f) A player kicks a football.

ii) In which of the above cases is momentum conserved?
iii) In which of the above cases is kinetic energy conserved?

Q11 Determine the momentum and the kinetic energy of objects of the following masses and velocities.

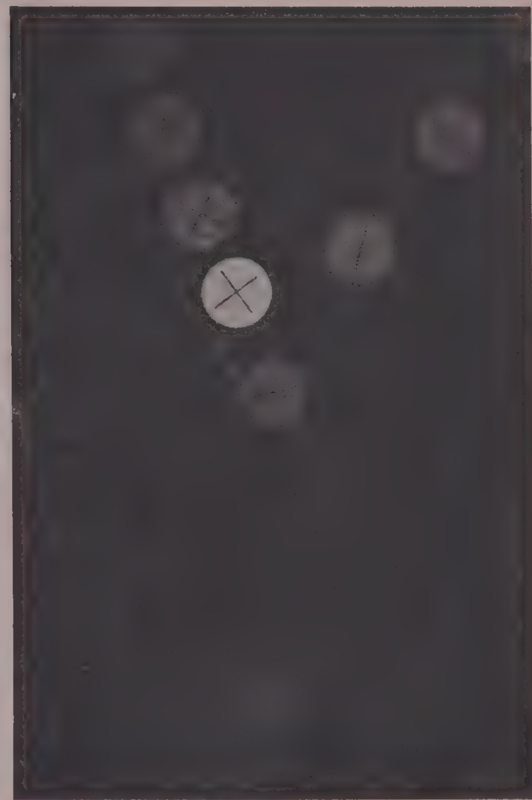
MASS	*VELOCITY*	$\vec{p}$	*KE*
a) 2 kg	3 m/s right		
b) 2 kg	3 m/s left		
c) 2 kg	6 m/s right		
d) 4 kg	3 m/s left		

See also Problem 10.23 on page 17.

A Collision in Two Dimensions

The stroboscopic photograph shows a collision between two wooden discs on a frictionless, horizontal table, photographed from straight above the table. The discs are riding on tiny plastic spheres which make their motion nearly frictionless. Body B (marked x) is at rest before the collision. After the collision it moves to the left and Body A (marked -) moves to the right. The mass of Body B is known to be twice the mass of Body A: $m_B = 2m_A$. We will analyze the photograph to see whether momentum was conserved. (Note: the size reduction factor of the photograph and the [constant] stroboscopic flash rate are not given here. So long as all velocities are measured in the same units, for this test it does not matter what those units are.)

In this analysis we shall measure in centimetres the distance the discs moved on the photograph. We shall use the time between flashes as the unit of time. Before the collision, Body A (coming from the lower part of the photograph) travelled 36.7 mm in the time between flashes: $\vec{v}_A = 36.7$ speed-units. Similarly we find that $\vec{v}'_A = 17.2$ speed-units, and $\vec{v}'_B = 11.0$ speed-units.



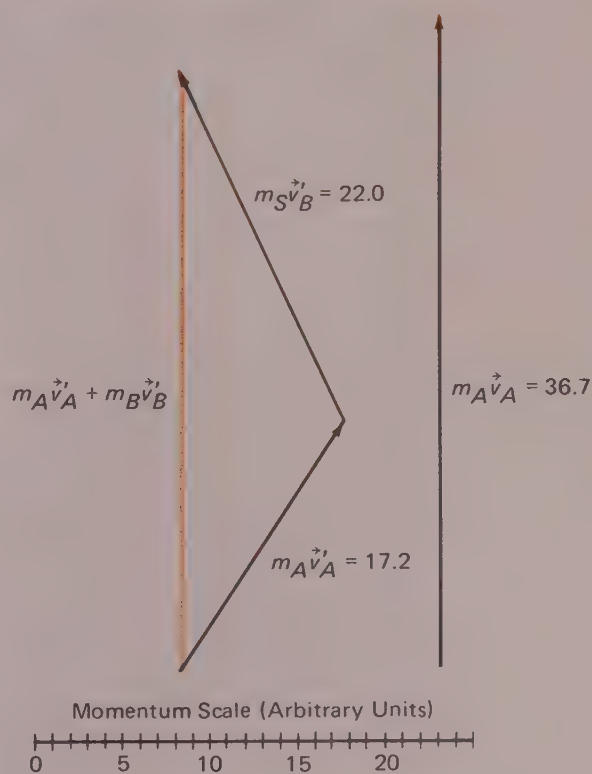
Film Loop 10.4, *Two-Dimensional Collisions.*

The total momentum before the collision is just $m_A\vec{v}'_A$; and is represented by an arrow 36.7 momentum-units long, drawn at the right.

The vector diagram at the left shows the momenta $m_A\vec{v}'_A$ and $m_B\vec{v}'_B$ after the collision; $m_A\vec{v}'_A$ is represented by an arrow 17.2 momentum-units long. Since $m_B = 2m_A$, the $m_B v'_B$ arrow is 22.0 momentum-units long.

The dotted line represents the vector sum of $m_A\vec{v}'_A$ and $m_B\vec{v}'_B$; that is, the total momentum after the collision. Measurement shows it to be 34.0 momentum-units long. Thus, our measured values of the total momentum before and after the collision differ by 2.7 momentum-units, a difference of about -7%. You can also verify that the direction of the total momentum is the same before and after the collision to within a small uncertainty.

Have we now demonstrated that momentum was conserved in the collision? Is the 7% difference likely to be due entirely to measurement inaccuracies, or is there reason to expect that in this experiment the total momentum of the two discs after the collision is really a bit less than before the collision?



Section A

10.1 Define an isolated system.

*10.2 You have been given a precise technical definition of the word momentum. Look it up in a large dictionary and record its various uses. Can you find anything similar to our definition in these more general meanings? How many of the uses seem to be consistent with the technical definition given here?

10.3 State the law of conservation of momentum.

10.4 Why is momentum important in nature?

10.5 A .01-kilogram bullet shot southward at 700 m/s, struck a 250-kg bear charging due north at 3.0 m/s. Find the momentum of each before the collision. Did the bear "stop in his tracks"? Why?

10.6 A gun of mass 8000 kg fires a 200 kg shell with a speed of 80 m/s. Calculate the recoil velocity of the gun.

10.7 If all the people in the world (about 3×10^9 people) were to stand together in one field and simultaneously jump upward with an initial speed of 3 m/s, what would be the earth's downward speed?

(The mass of the earth is approximately 6×10^{24} kg.)

10.8 A cart shoved along a flat table comes to a rest in two seconds. What has happened to its momentum?

10.9 A freight car of mass 10^5 kg travels at 3.0 m/s and collides with a freight car of mass 2.0×10^5 kg on a horizontal track. The two cars lock, and roll together after impact. Find the velocity of the two cars after collision.

10.10 Two bodies A and B, with masses $m_A = 5.0$ kg and $m_B = 2.0$ kg are travelling in the same direction, A with a speed of 2.0 m/s, and B with a speed of 1.0 m/s. A catches up with B, sticks to it, and the two move on together. What is their common velocity after impact?

10.11 A hard steel ball of unknown mass suspended at the end of a long string is struck head-on by another steel ball of mass 1.0 kg suspended in a similar manner. The moving ball had an initial velocity of 5.0 m/s to the right and it rebounded with a velocity of 4.0 m/s to the left. The stationary ball moved off to the right with a speed of 1 m/s. What was its mass?

10.12 Two soft putty balls, A with mass $m_A = 1.0$ kg and B with mass $m_B = 3.0$ kg, strike each other with velocities $\vec{v}_A = 0.17$ m/s to the right and $\vec{v}_B = 0.15$ m/s to the left. They stick together on impact. What is their common velocity just after impact?

*10.13 (a) List different ways in which the law of conservation of momentum can be expressed algebraically. Show that they are equivalent to each other.

(b) Show algebraically that "force" may be defined as the rate of change of momentum.

*10.14 Newton's second law can be written $\vec{F}\Delta t = m\Delta\vec{v}$. Use the second law to explain the following:
a) It is safer to jump into a fire-net or a load of hay than onto the hard ground.
b) When jumping down from some height, you should bend your knees as you come to rest, instead of keeping your legs stiff.
c) Hammerheads are generally made of steel rather than rubber.
d) Some cars have plastic or water bumpers which are temporarily deformed under impact, slowly return to their original shape. Others are designed to have a somewhat pointed front-end bumper.

10.15 A rubber ball and a ball made of soft putty have equal masses and equal momenta when they hit a vertical wall. Which ball transfers a greater amount of momentum to the wall?

*10.16 a) A ball falls from a boy's hand, hits the ground and rebounds almost back up to his hand. What are the momentum changes related to this during this time?
b) Imagine that the ball was comparable in mass to the mass of the earth. What differences would this make to your discussion?

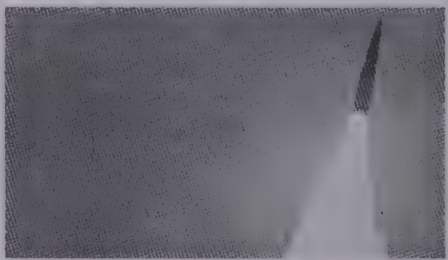
*10.17 Two boys on ice skates, and of equal mass, hold onto a rope. What can you say about their motions if one boy pulls on the rope? Why?

*10.18 a) A man is standing motionless in the centre of a large flat, frictionless surface. How can he get himself to shore? Explain the principle involved.
b) Suppose the same man was in motion and he wanted to stop. How could he?
c) Although the situations in parts a) and b) were imaginary, there are times when astronauts in space have used the principles involved. Can you state how?

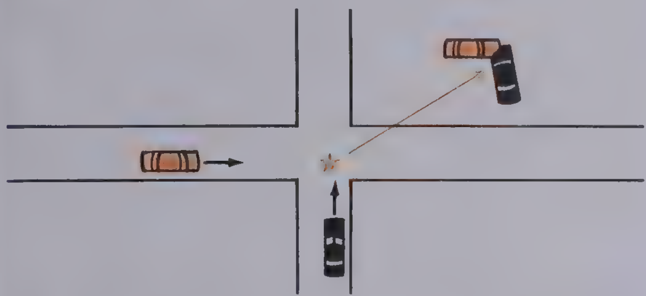
*10.19 A boy stands at rest on the earth and holds a ball in his hand. (The momentum of the ball and his hand are both zero.) He then throws it straight up in the air. At the instant it leaves his hand he points out that both the ball and his hand have an upward momentum and therefore claims that momentum has been created and the Law of Conservation of Momentum is not valid. What do you think? Explain. Can you prove your assertion?

*10.20 Why do ocean-going ships take a long time to execute 90° turns.

*10.21 Discuss the photo from the point of view of conservation of momentum.



*10.22 A police report of an accident describes two vehicles colliding (inelastically) at a right-angle intersection. The cars skid to a stop as shown. Suppose the masses of the cars are approximately the same. Which car was travelling faster at collision? Why?



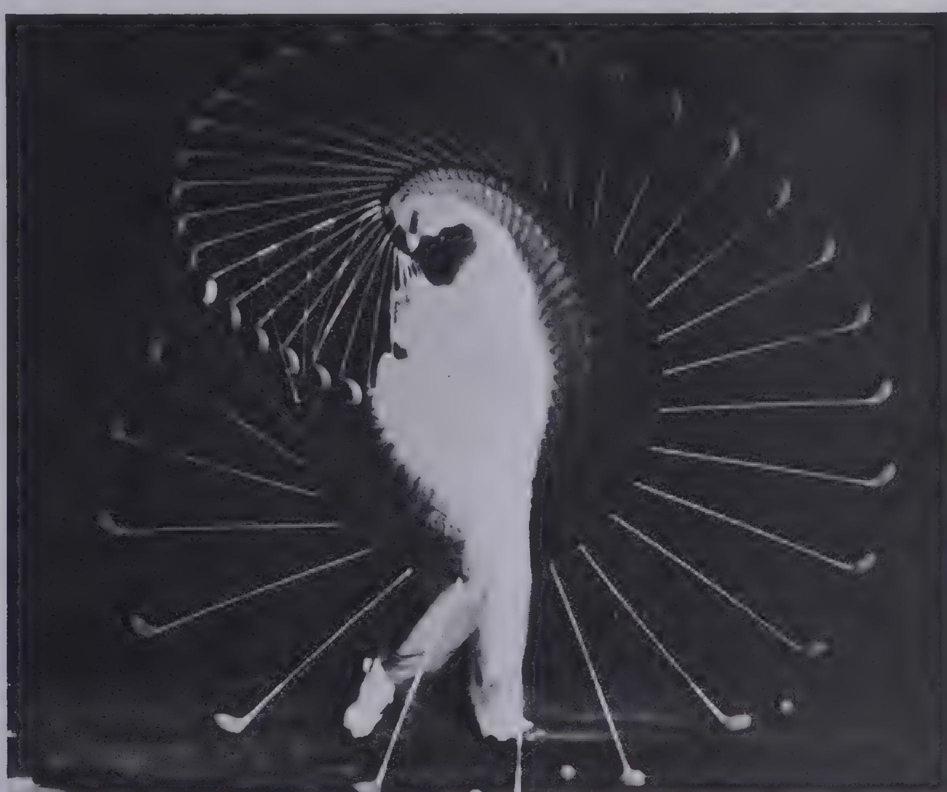
10.23 Which of the collisions represented in problems 10.9 to 10.12 do you think are elastic and which do you think are inelastic? Check your prediction by calculating the kinetic energy before and after the collision in at least two of these problems. (Try at least one that you think is elastic and one you think is inelastic.)

Section B

10.24 During some sports, the forces exerted on parts of the body and on the ball, etc., can be astonishingly large. To illustrate this, consider the forces in hitting a golf ball. Assume the ball's mass is .046 kg. From the strobe photo Fig. 10.3, in which the time-interval between strobe flashes was 0.01s, estimate:
a) the speed of the ball after impact,
b) the magnitude of the ball's momentum after impact,
c) how long the impact lasted,
d) the average force extended on the ball during impact.

*10.25 A student in a physics class, having learned about elastic collisions and conservation laws, decides that he can make a self-propelled car. He proposes to fix a pendulum on a cart using a "super-ball" as a pendulum bob. He fixes a block to the cart so that when the ball reaches the bottom of the arc, it strikes the block and rebounds elastically. It is supposed to give the cart a series of bumps that propel it along.
a) Will his scheme work? (Assume the "super-ball" is perfectly elastic.) Give reasons for your answer.
b) What would happen if the cart had an initial velocity in the forward direction?
c) What would happen if the cart had an initial velocity in the backward direction?

10.26 One ball, of mass m_1, and velocity $\vec{v}_1$, strikes a second ball of mass m_2 which was initially at rest. The collision is head-on, and almost perfectly elastic. Derive expressions for the velocities of ball 1 and ball 2 after the collision. (Remember, *both* momentum and kinetic energy are conserved.)



Chapter 11 *Energy*

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Energy

Chapter Eleven

11.1 Energy

The term energy is a commonly used word in our society. Children are described as being "full of energy". Breakfast cereals are advertised as good sources of energy. Modern man's need for energy and the effects that acquiring it have had on the environment are important issues of our times.

Energy is also a key word in any study of science. If you ask a scientist "What is the single most important law of nature? " he would probably answer, "The law of conservation of energy". If you then pressed him to describe what energy is, he would give you many examples of the various forms it can take, or equations to let you calculate how much of it there is in various circumstances. But he would have difficulty explaining exactly what it is. In this chapter we are going to study the important and interesting concept that scientists call energy.

Energy has come to be closely associated with the idea of work. A body that has the ability to do work is said to have energy. In fact the most usual definition for energy is: *Energy is the ability to do work.*

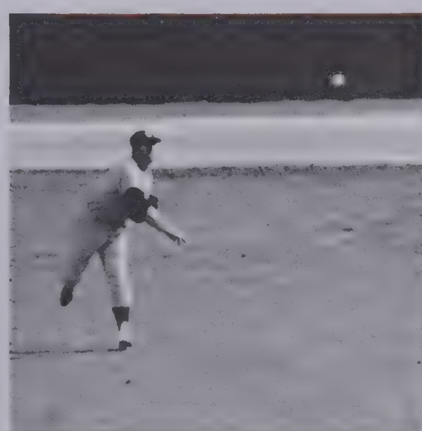
Let us develop an understanding for the term "work".

Some forms of Energy
- Mechanical
- Heat
- Sound
- Light
- Radiant
- Electrical
- Nuclear
- Chemical
- Mass-energy

The word *Energy* is derived from two Greek words:

en — in
ergon — work

Activity 11.1, *Energy Transformations.*



11.2 Work

In everyday language we say that we are "playing" when we are pitching, catching, and running on the baseball field; when we are sitting at a desk solving physics problems, we are "working". A physicist would disagree. He would say that while studying we are doing very little work, whereas on the softball field we are doing a great deal of work. "Doing work" means something very

definite to a physicist: it means "*exerting a force on an object while the object moves in the direction of the force*". Thus when you throw a softball, you exert a large force on it while it moves forward about a metre; you do a large amount of work. By contrast, turning pages of a textbook requires you to exert only a small force, and the pages do not move very far; you do not do much work.

Suppose you are employed in a factory to lift boxes from the floor to a conveyor belt at waist height. Both you and the physicist would agree that you are doing work. It seems like common sense to say that if you lift two boxes at once, you do twice as much work as you do if you lift one box. It also seems reasonable to say that if the conveyor belt were twice as high above the floor, you would do twice as much work to lift a box to it. The work you do depends on both the magnitude of the force you must exert on the box and the distance through which the box moves.

In physics we say that work has been done on a body only if two conditions are met.

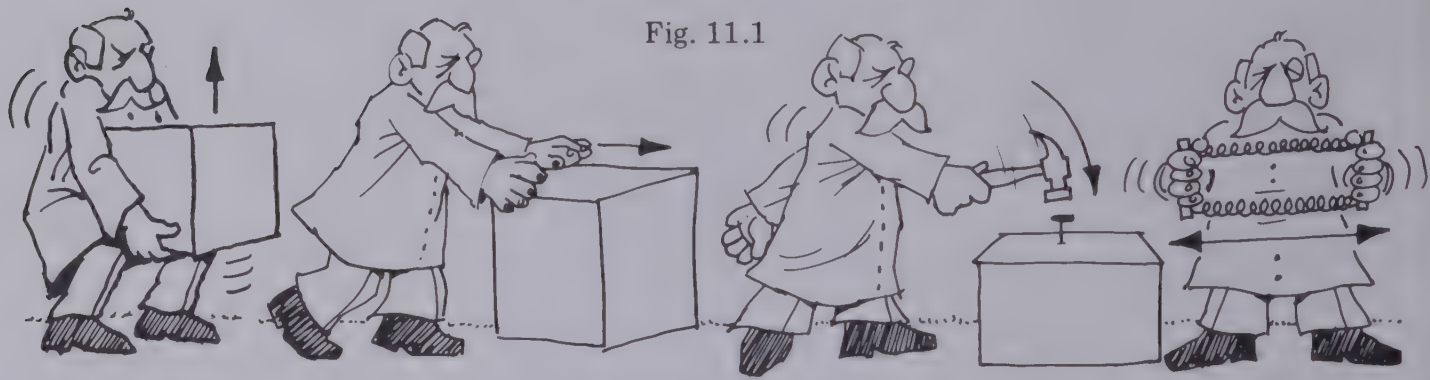
1. A force must act on a body.
2. The body must move in the direction of the force.

Note that the work you do does not depend on how fast you do your job.

The work done by a force on a body *is equal to the product of the force exerted times the distance moved in the direction of the force.*

$$W = Fd.$$

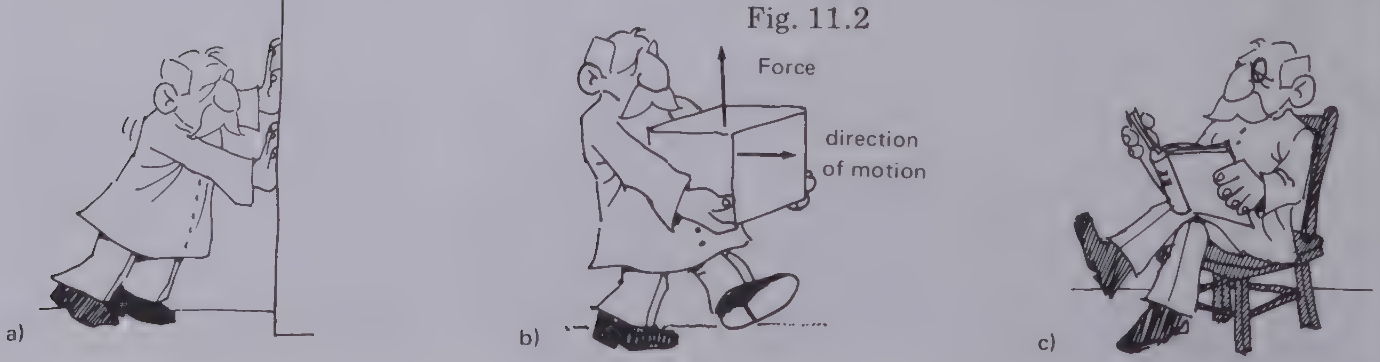
Fig. 11.1



To decide whether work is done in these cases, we must ask, "Did a force move a body in the direction of the force?" If it did, then work was done. In each of these cases the answer is yes.

Now consider these situations:

Fig. 11.2



Again we apply the same rules to decide if there is work being done.
a) No work is done on the wall because there is no motion of the box.
b) No work is done on the box. The force exerted by the man is vertical, the direction the object is moving is horizontal. The force and motion are not in the same direction.
c) Although the man would say he is working, he is not doing work in the physical sense. He exerts no force which moves a body through a distance.

Often, beginning students of physics object to these conclusions. They will admit that no work is being done according to the definition of work, but feel that work has been done in these cases in spite of the definition. They suggest the definition is an illogical one. If you should feel this way, we ask you to wait until we have developed the ideas of energy further. Only then can you understand why scientists accept this definition for work.

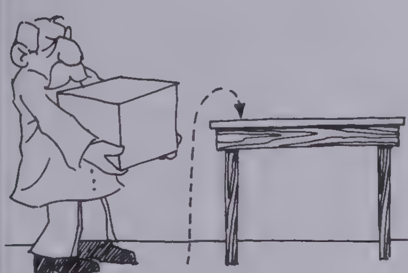
The units in which the concepts work and energy are measured are determined by the way in which we define work. Since work is defined as the product of a force and a displacement, the units in the metric system are newtons times metres or newton-metres. If a one newton force is exerted on a body and moves it one metre, we say that one newton-metre of work has been done by the force. This unit is a little awkward and a new unit has been defined called a **joule**. *One joule equals one newton-metre.*

The name of the unit of energy and work commemorates J. P. Joule, a nineteenth century English physicist, famous for his experiments showing that heat is a form of energy. The word is pronounced as "jewel."

Example Problem

A man lifts a box with a weight of 100 newtons from the floor to a table top 1. 2 metres above the floor. How much work did he do on the box?

Force required to just lift a weight of 100 newtons = 100 N.
Distance moved in direction of force = 1.2 m,



$$\therefore \text{ work done} = Fd,$$
$$= (100\text{ N})\,(1.2\text{ m}),$$
$$= 120 \text{ newton-metres},$$
$$= 120 \text{ joules}.$$

Fig. 11.3

Q1 Define 1 joule of work.
Q2 In what conditions can a force act on a body and yet do no work on it?
Q3 Determine the work done by the force on the body in the following circumstances.
a) A 5-newton force applied to a body moves it 3.0 metres.

b) A baby with mass 15 kilograms is lifted 1.5 metres from the floor.

c) A 10-kilogram model rocket is accelerated upward through 100 metres by an average thrusting force of 2000 newtons.

d) A 1000-newton hammer blow drives a nail 6 millimetres into a board.

e) A man supports a 10-kg mass 1 metre above the floor for 30 minutes.

Q4 A body moves 3 metres while 30 joules of work is done on it. What is the average force exerted during this time?

See also Problem 11.1 on page 43.

11.3 Power

It is not always just the amount of work done by some source that is of concern. If we must choose between two sources of energy, we may be inclined to favour one that can do a job faster. *The rate at which an energy source does work is called the* **power** *of the source.*

Experiment 11.1, *Power of a Motor.*

$$P = \frac{W}{T}.$$

If a source of energy performs work at the rate of one joule each second, then that source is said to have a power of one watt.

$$1 \text{ watt} = \frac{1 \text{ joule}}{1 \text{ second}}.$$

In the previous example problem, if the boy took two seconds to perform the task of lifting the box to the table, then he was working at a power of:

$$\text{Power} = \frac{\text{work done}}{\text{time taken}}.$$

$$P = \frac{W}{T} = \frac{120 \text{ joules}}{2 \text{ seconds}},$$

$$= 60 \text{ watts}.$$

The watt is a unit named after James Watt (1736-1819), the Scotsman who developed the first efficient steam engine.

The horsepower is another commonly used unit of power. 1 horsepower = 746 watts.

Table 11.1 shows the power ratings of some common appliances and machines.

Table 11.1

Energy Output Device	Power (Rate of Energy Output in watts)
100-watt light bulb	100 w
Electric toaster	1000 w
Electric kettle	1500 w
Clothes dryer	4000 w
Electric oven element	8000 w
Cadillac Eldorado	2.6×10^5 w

Q5 What is the power of an electric motor that can do 150 joules of work in 5 seconds?
Q6 What is the power of a motor for a hoist that will lift a 200-kg object through 10 metres in 10 seconds?
Q7 How long would it take a 3.0-kilowatt motor to raise a 500-kg crate 6.0 metres?
Q8 How much energy is consumed when an 800-watt dryer element in an electric dishwasher operates for 5 minutes?
See also Problems 11.2 to 11.4 on page 43.

11.4 Kinetic Energy

Suppose that a person were to do work on the cart in Fig. 11.4 by exerting a force of three hundred newtons on the cart through a distance of one metre. He would then have done an amount of work equal to

Experiment 11.2, *Energy of a Moving Object.*

$$\begin{aligned} W &= Fd, \\ &= 300 \text{ newtons} \times 1 \text{ metre}, \\ &= 300 \text{ joules.} \end{aligned}$$

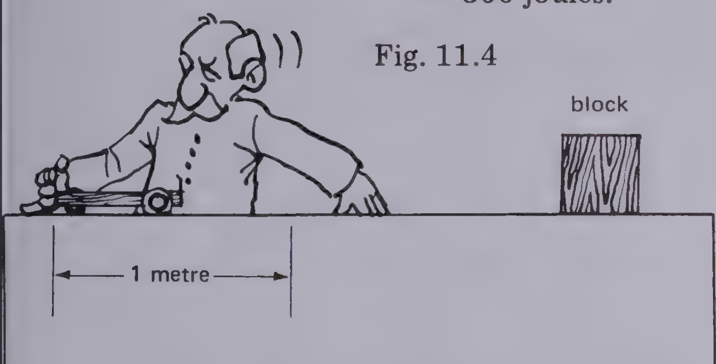


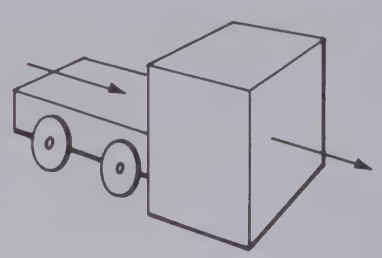
Fig. 11.4

When he stops applying the force (assuming the surface is flat and frictionless), the cart will move with a constant velocity. This moving cart now has the ability to do work on the block in its path. That is, it can exert a force on the block and move it through a distance. We say the cart has energy—the ability to do work. This cart has energy associated with its motion. It has a form of energy called kinetic energy.

At various times in this course we have seen different ways of describing properties of moving objects, for example, speed (v), velocity ($\vec{v}$), momentum ($m\vec{v}$), and the property that seventeenth century thinkers called vis visa (mv^2). Now, through the concepts of work and energy, comes a different description, called *kinetic energy*.

It can be shown in a few lines of algebra that the work done by a force (F) over a distance (d) on a body of mass (m) initially at rest on a frictionless surface, causes it to achieve a final speed (v) such that,

$$\text{work done} = Fd = \tfrac{1}{2}mv^2.$$



The quantity one-half the product of the mass times the square of the speed of a body is called the **kinetic energy** *of a body.*

$$KE = \frac{1}{2}mv^2.$$

The work done on a body on a frictionless surface goes entirely into increasing the kinetic energy of a body.

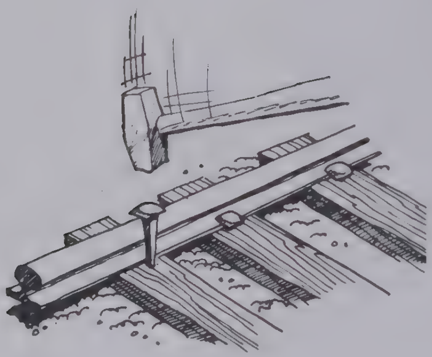
The equation $Fd = \frac{1}{2}mv^2$ was obtained by considering the case of an object initially at rest, that is, with an initial kinetic energy of zero. More generally, the object may already be in motion when the net force is applied. In that case the work done on the object equals the change in its kinetic energy:

$$W = \frac{1}{2}mv^2{}_f - \frac{1}{2}mv^2{}_i,$$

$$W = KE_f - KE_i,$$

$$= \Delta KE.$$

If the mass of a body (m) is expressed in kilograms and its speed (v) in metres per second, the kinetic energy (KE) will be in joules.



Example Problem

Calculate the kinetic energy of a hammer of mass 3.0 kg while being swung at a speed of a) 4.0 m/s b) 8.0 m/s.

a) $KE = \frac{1}{2}mv^2$

$$= \frac{1}{2}(3)\text{ kg }(4)^2\ \frac{\text{m}^2}{\text{s}^2},$$

$$= \frac{1}{2}(3)\ (16)\text{ kg }\frac{\text{m}^2}{\text{s}^2},$$

$$= \frac{1}{2}(48)\text{ kg }\frac{\text{m}^2}{\text{s}^2},$$

$KE = 24$ joules.

b) $KE = \frac{1}{2}(3)\text{ kg }(8)^2\frac{\text{m}^2}{\text{s}^2},$

$$= \frac{1}{2}(3)\ (64)\text{ kg }\frac{\text{m}^2}{\text{s}^2},$$

$KE = 96$ joules.

Notice that although the speed of the hammer has only doubled from 4 m/s to 8 m/s, its kinetic energy is four times larger. This is because the kinetic energy of an object is proportional to the *square* of its speed. Doubling the speed increases kinetic energy by $(2)^2 = 4$ times. Tripling the speed increases kinetic energy by $(3)^2 = 9$ times!

Q9 Compute the kinetic energy of the following:

a) a 0.4-kg baseball thrown at 30 m/s,

b) a 1000-kg rhinoceros running at his top speed of 15 m/s,

Work and Kinetic Energy

Suppose a horizontal force F_{app} is applied over a distance (d) to a box initially at rest on a frictionless surface. The amount of work done on the box by this force equals $F_{app}d$. Let us see if we can relate this expression to the mass and speed of the box after it travels the distance (d).

Since the applied force is the only horizontal force acting, it is also the net force.

$F_{app} = F_{net}$ ($\because$ no friction)

Now, this constant net force produces a constant acceleration, and, since the body starts at rest, we can say that

$d = \frac{1}{2}aT^2$.

Where T is the time for which the force is applied.

But the speed of the body after time T has elapsed is equal to,

$$v = aT.$$

Therefore $T = \frac{v}{a}$.

Substituting for T,

$$d = \frac{1}{2}a\,\frac{v^2}{a^2},$$

or, $$d = \frac{1}{2}\,\frac{v^2}{a}.$$

Now, the work done on the box is,

$$W = F_{app}d.$$

$\therefore$ $W = (ma)d$. ($F_{app} = F_{net} = ma$).

Substituting for d,

$$= ma\,\frac{1}{2}\frac{v^2}{a}.$$

$$W = \frac{1}{2}mv^2.$$

That is, the work done by the force on the box exactly equals the quantity that we call kinetic energy. With more advanced mathematics it can be shown that the result is the same whether the force is constant or not.

c) a 1500-kg automobile moving at 30 m/s.

Q10 If a 10-kg object has a kinetic energy of 20 joules, what is its speed?

*Q11 Show that the unit newton-metre is the same as the unit kg$\frac{m^2}{s^2}$.

See also problems 11.5 to 11.7 on page 43.

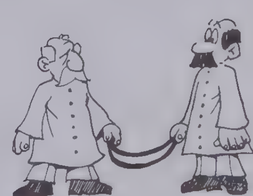
11.5 Potential Energy

Suppose physical work is done on a spring or an elastic by stretching them, or that an object is lifted off the floor. In each case work has been done on the bodies because an object has been moved in the direction of a force. We say that energy has been transferred to each of the objects. They now have the ability to do work. (Considering what happens when a stretched spring or elastic is released, or when the object falls to the floor, should convince you that they have energy.)

But this time their energy is dependent on their position, not on their motion. If the elastic or the spring were not stretched so that the ends changed position with respect to each other, or the object were resting on the floor rather than held above it, they would not have the ability to do work. *This energy due to the position of an object is called* potential energy.

We often describe many different types of potential energy. The names of the types usually refer to the kinds of forces involved as the position of the body changes. For instance consider these examples:

a) There is *elastic potential energy* stored in the system of the two men and the elastic. Work must be done to extend the elastic. The system now has the ability to do work.



a)

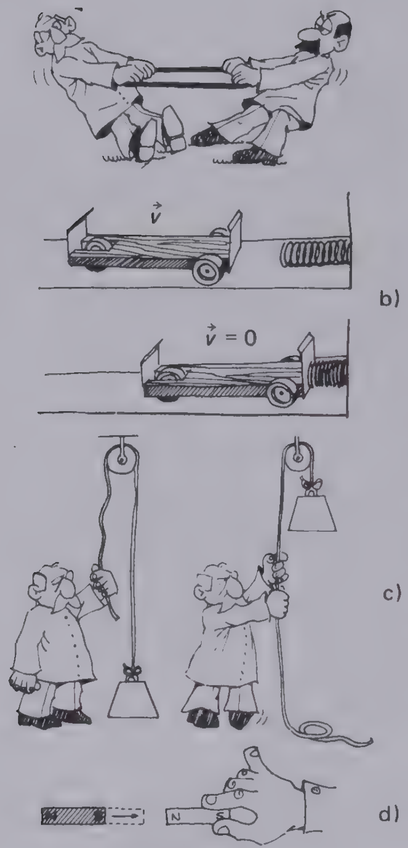


Fig. 11.5

b) The cart does work in compressing the spring. We say the system gains *spring potential energy*.
c) The earth-box system gains *gravitational potential energy*.
d) This system gains *magnetic potential energy*. Work has been done in separating the magnets.

In each example the systems have the ability to do work, but they are not actually doing the work at the time of the drawings. Their energy is stored as potential energy.

Where is the potential energy located in all these cases? It might seem at first that it "belongs" to the body that has been moved. But this is not the most useful way of thinking about it. Consider that without the other object—the other man in a), the wall in b), the earth in c), the other magnet in d)—the work would not have increased any form of potential energy; it would have just increased the kinetic energy of the object on which work was done. The potential energy belongs not to one of the bodies that interact, but to the whole system of interacting bodies! This is evident in the fact that the potential energy is available to any one or to all of these interacting bodies. For example, either magnet could be given all the kinetic energy, just by releasing it and holding the other in place. If the book could be fixed somehow to a hook that would keep the box at one point in space, the earth would "fall" up toward the box, eventually gaining just as much kinetic energy at the expense of the stored potential energy, as the box would have gained if it were free to fall. But because the earth's acceleration would be much smaller it would take a very long time. For this reason, when referring to gravitational potential energy, we often assume that the gravitational potential energy "belongs" to the object being lifted, when, strictly speaking, it is shared in the earth-object system.

During its contact with a golf club, a golf ball is distorted, as is shown in the high-speed photograph. As the ball moves away from the club, the ball recovers its normal spherical shape, and elastic potential energy is transformed into kinetic energy.

*Q12 How does *PE* differ from *KE*?

Q13 Suggest two ways that you could increase the potential energy of a coiled spring.

Q14 Two positively charged objects repel one another. To increase the electric potential energy, you must
a) make the objects move faster.
b) move one object in a circle around the other object.
c) attach a rubber band to the objects.
d) pull the objects farther apart.
e) push the objects closer together.

*Q15 List as many different kinds of potential energy as you can. What do they all have in common?

See also Problem 11.8 on page 43.

11.6 Gravitational Potential Energy

Since ancient times, man has realized that he could use the force of gravity to do work. The gravitational potential energy of the water in Fig. 11.6 is converted to kinetic energy which does work in spinning the paddle wheel. This, in turn, moves the blades of a saw wheel inside the building.

To calculate the amount of gravitational potential energy a body has when it is lifted above the ground, we rely on the connection between physical work and energy.

The energy transferred by a force to a body is equal to the work done on the body.
Therefore, if we calculate the work done in just lifting a body through a certain distance, we will be able to call our answer the amount of gravitational potential energy in the body.

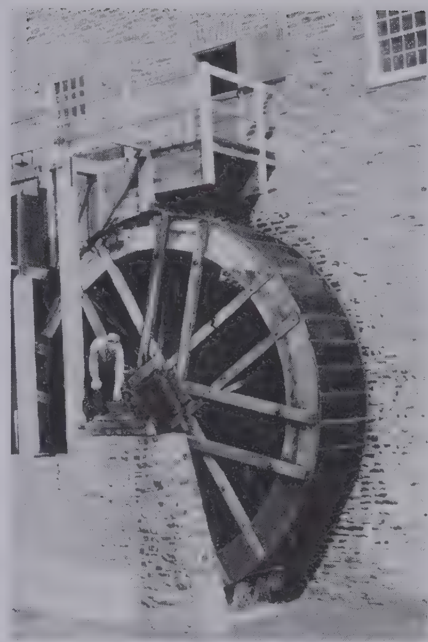


Fig. 11.6

Example Problem

A man must lift a heavy box weighing 500 newtons from the ground to the table, then lift it into the truck from there.

a) What is the potential energy of the box with respect to the ground when he has lifted it to the table?

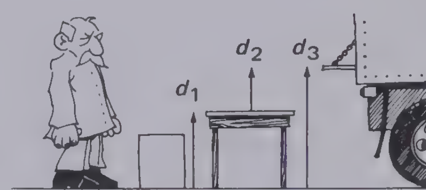
Work done in lifting from ground to table
= *PE* with respect to ground,
= Fd_1,
= (500N) (1.5m),
= 750 joules.

b) What is the *PE* of the box with respect to the table top when he has lifted it to the truck?

Work done in lifting the table to the truck
= *PE* with respect to the table top,
= Fd_2,
= (500N) (1.0m),
= 500 joules.

c) What is the *PE* of the box with respect to ground when it is in the truck?

Work done in lifting box from ground to truck
= *PE* with respect to ground,
= Fd_3,
= (500N) (2.5m),
= 1250 joules.

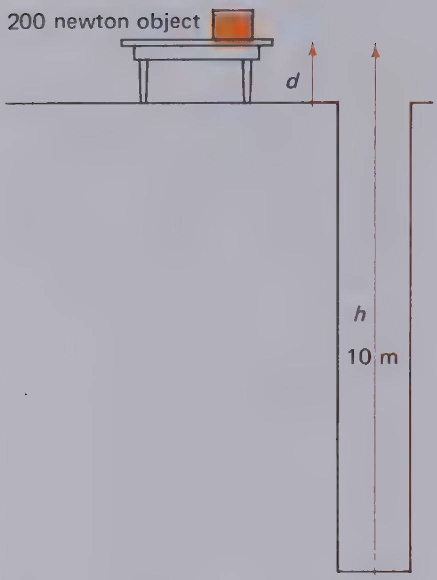


wt. = 500 N

d_1 = 1.5 metres
d_2 = 1.0 metres
d_3 = 2.5 metres

Notice that the gravitational potential energy of the box with respect to the ground when it is in the truck will be the same no matter how it gets to the truck.

One further point should be made. When stating the gravitational potential energy of a body, we must always specify a reference level. This is often the lowest level at which the body would likely be found. The potential energy of the body at this reference level is taken to be zero. This makes sense, since a body has no ability to do work on another body at the same level. The reference level might be on the ground, at the top of a table, or even at the bottom of a well. For example, if we lift a body 1 metre from the floor to the top of a table by exerting a force of 200 newtons, then the body has 200 joules of potential



energy *with respect to the floor*. However, that body might be 10 metres above the bottom of a hole under the table. Then the potential energy of the body would be 2000 joules *with respect to the bottom of the hole.*

Q16 When a person lifts a body off the ground, why do we say the gravitational potential energy of the body increases?
Q17 A golf ball has a mass of .05 kg. Calculate the gravitational potential energy of two golf balls 1 metre from the floor.
Q18 If a 5-kg object has a gravitational potential energy of 100 joules with respect to a table top, how high above the table top is it?
Q19 Explain how a body can have more than one value for its gravitational potential energy at any one time.
See also Problems 11.9 and 11.10 on page 43.

11.7 Conservation of Mechanical Energy

Experiment 11.3, *Energy of a Falling Object.*

Gravitational potential energy and kinetic energy were the first two forms of energy to be defined. They are forms of what has come to be called **mechanical energy.** An as object falls from a position above the earth's surface, potential energy is continuously converted to kinetic energy. From the way in which these forms of mechanical energy are defined, the gravitational potential energy in a body while suspended above the earth *must* become *completely converted* into kinetic energy just as it is about to hit the earth. The proof of this for a falling ball is outlined below.

Assume the force of friction acting on the ball is negligible. Then the only force acting on the body is the force of gravity and the body will fall with the free fall acceleration.
The speed of ball just before hitting ground, v_f, is
$v_f = v_i + aT$

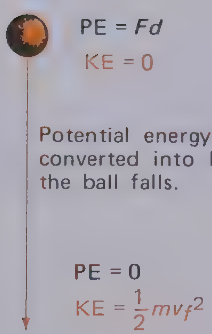
and Eqn. 1 $v_f = a_g T$ (since $v_i = 0$).
The distance the ball has fallen can be expressed as

$$d = \frac{(v_i + v_f)\,T}{2},$$

or

$$d = \frac{(v_f)\,T}{2},$$

Eqn. 2 $\therefore$ $v_f = \dfrac{2d}{T}$.



Potential energy is continuously converted into kinetic energy as the ball falls.

Now, the kinetic energy of ball just before hitting ground is

$$KE_{\text{bottom}} = \frac{1}{2}mv_f^2$$

or,

$$= \frac{1}{2}\,(m)\,(v_f)\,(v_f).$$

Substituting from Eqns. 1 and 2, $= \frac{1}{2}(m)(a_g T)(\frac{2d}{T})$

$$= ma_g d.$$

But, $F = ma_g$

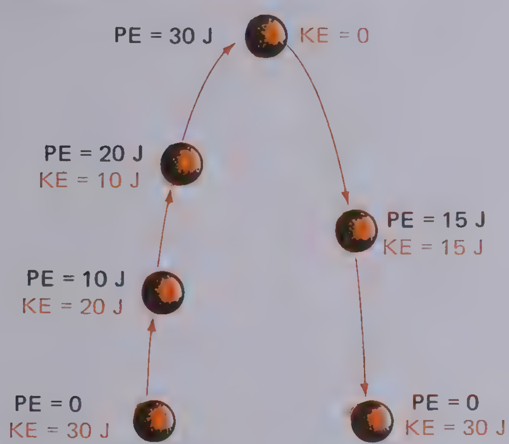
Therefore, KE at bottom $= Fd$

$= PE$ at top.

The conclusion we can draw from this is that in this sytem the total mechanical energy just before the body starts to fall is just equal to the total mechanical energy just before it hits the ground. A more detailed analysis of the mechanical energy in the system at positions between these two extremes, would show that the total mechanical energy is constant at all times during the fall.

This is true also if the body were initially thrown vertically upward. At first all its energy, let us suppose it is 30 joules, is kinetic. As it rises, its potential energy increases at the expense of its kinetic energy. For each joule of kinetic energy lost, it gains one joule of potential energy. At the highest point in the path, all 30 joules of energy is in the form of potential energy. On the downward part of the trip, potential energy is continuously converted to kinetic energy. The total mechanical energy remains constant at 30 joules. For mechanical energy to be conserved $KE + PE =$ a constant.

Activity 11.4, *What's in a Spring.*



In this system of ball and earth, the gravitational force must be the only force acting during the flight. The force of friction must be so small as to have a negligible effect on the motion of the ball. Systems in which the force of friction either does not act, or is so small that it is neglected, are called *conservative systems.*

In a **conservative system**, *the sum of the kinetic energy and potential energy at any time is a constant.*

Notice that the derivation of the expression for kinetic energy relies only on

1) the definition of work,

2) Newton's second law of motion,
3) a kinematic equation.

The expression for gravitational potential energy involves just the definition of work and Newton's second law.

The point here is that these expressions, and the entire concept of mechanical energy, are just new ways of describing behaviour of bodies. Mechanical energy forms do not represent the discovery of new physical behaviour, but are just new ways of combining old relationships to provide a new way of describing interactions.

The value in this particular combination is that the property of energy conservation makes otherwise very difficult problems relatively easy to solve. Truly conservative systems very rarely exist in nature, since the force of friction cannot be reduced to zero. But we have found by experience that the answers computed by assuming systems with little friction are conservative systems, are close enough to reality to be of use.

Activity 11.5, *Energy of a Pendulum.*

Example Problem

A pendulum 3.0 metres long with a 4.0-kilogram bob is pulled aside so that it is 1.25 metres above its lowest point and then released. What speed does it have at the lowest point in its swing?

To calculate its speed from Newton's second law and kinematic equations would be difficult, because the force acting on the bob changes at each point in its swing. But, assuming the system is conservative, and using the law of conservation of mechanical energy, we can say that

KE at lowest point = *PE* at start.

$\therefore \frac{1}{2}mv^2 = Fd.$

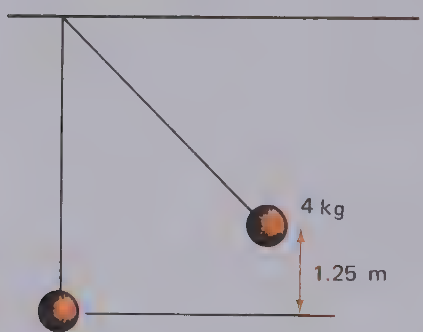


Fig. 11.7

$\frac{1}{2}$ (4 kg) (v^2) = (40 N) (1.25 m)

$\therefore$ 2 kg (v^2) = 50 N-m.

$v^2 = \frac{50}{2} \frac{\text{N-m}}{\text{kg}},$

$v^2 = 25 \frac{\text{kg m}}{\text{s}^2} \frac{\text{m}}{\text{kg}},$

$v^2 = 25 \frac{\text{m}^2}{\text{s}^2},$

$v = 5\frac{\text{m}}{\text{s}}.$

The speed of the stone at the bottom of the arc is 5 metres per second.

Q20 As a stone falls (neglecting friction)
a) its kinetic energy is conserved.
b) gravitational potential energy is conserved.
c) kinetic energy changes into gravitational potential energy.
d) no work is done on the stone.
e) there is no change in the total mechanical energy.

*Q21 What is meant by a conservative system? Give some examples of systems that you feel could be considered conservative.

See also Problems 11.11 to 11.18 on page 43.

.8 Another Look at the Definition for Work

Now that we have discussed forms of mechanical energy, we re in a better position to understand the reasons that physical ork is defined as it is. We say that *a force does work on a body henever that force changes the energy of the body.*

a) If an upward force applied to a body moves it vertically, hen the force is said to be doing work on the body because the otential energy of the body increases.

b) The force of gravity does work on a falling body, ncreasing its kinetic energy.

c) Holding a body above the ground may be tiring, but no ork is done by the force suspending the body because there is o increase in the mechanical energy of the body.

d) A horizontal force does work on an object on a rictionless surface by increasing the object's kinetic energy.

e) A man carrying a suitcase along a level surface at onstant speed exerts an upward force but no horizontal force. he suitcase does not increase its speed, and its kinetic energy, herefore, does not increase. We would want our calculation of he amount of work done by the force of the man on the suitcase o yield the answer zero, and it does because the force exerted is ot in the direction of motion of the suitcase.

*Q22 Refer to the concept of mechanical energy to discuss reasons why physical work is done or not done in Figs. 11.8a) and 11.8b).

*Q23 Work is done by a force on a book as it is pushed along a rough table. The force is removed as the book slides to a stop. What has happened to the work done by the force?

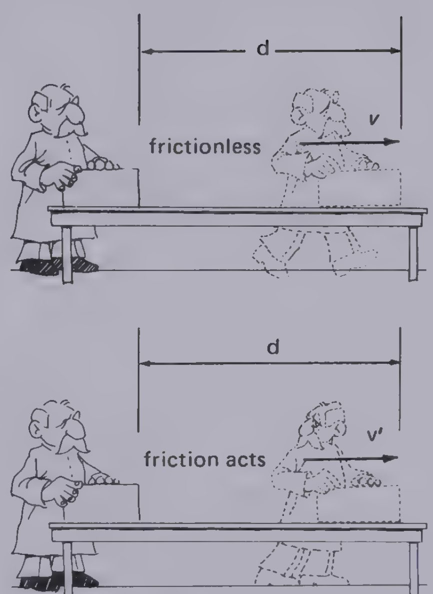


Fig. 11.8

.9 What Happens When Friction Acts?

On page 25 we saw that the work done by a force pushing a dy along a flat frictionless surface went entirely into kinetic ergy of the body. Let us suppose the man in Figs. 11.8a) and .8b) pushes the boxes with the same force in each case; in a) ere is a frictionless surface but in b) friction acts between the ble and the box. The speed the box achieves after moving a

The speed of the box is less in b) than in a) because friction opposes the motion in the second case.

distance (d) will be less than it is in case a) where no friction acts. Therefore the kinetic energy of the box in b) after moving the distance d, is less than in case a). The man has done the same amount of work on the box because he exerted the same force over the same distance d, but less kinetic energy has been transferred to the box. Does this mean that some of his work, that is, some of his energy, has disappeared? A reliable answer to this question is not at all obvious and was a matter of controversy for many years. It was eventually shown in a series of great experiments by James Joule in the 1840's, that the heat produced between the surfaces is just a form of energy. We now accept that the amount of heat energy (and perhaps sound energy) produced just exactly accounts for the "missing" energy.

Again, we argue that the amount of work done by the force on the box is equal to the energy transferred from the man to the cart but this time only part of that energy actually remains with the box—the rest is shared as heat between the box and the surface it slides on.

Activity 11.3, *Launching Pennies.*

Whenever the force of friction acts between moving bodies, some amount of any work being done on one body goes into the production of heat energy instead of into mechanical energy of the body alone. To visualize our modern view of how frictional forces result in the transformation of mechanical energy into heat energy let us look at a simple example.

When a box is given a shove across a horizontal table top, it soon comes to rest. The mechanical energy is converted into heat. To understand the process we must realize that although the box appears to lie flat on the table, if we were able to enlarge the surfaces we could see that each is very rough; and contact is made in only a few places. If we were able to magnify one region millions of times where there is "contact", we would be able to "see" the box and table surface on an atomic scale.

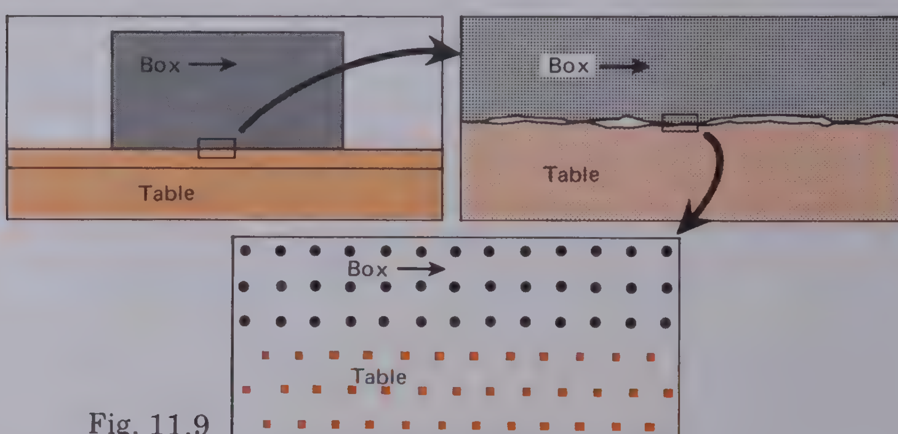


Fig. 11.9

Various scale views of the contact of a box and a table. At one of the points of contact, y, the scale is greatly enlarged so that the molecules can be seen. They are in different, but regular, arrays, held in place by electrical forces between the molecules.

We must visualize that the molecules in each region jiggle back and forth through small distances even when the objects themselves are at rest. Of course the molecules of the box and table are not really shaped like dots and squares, but the

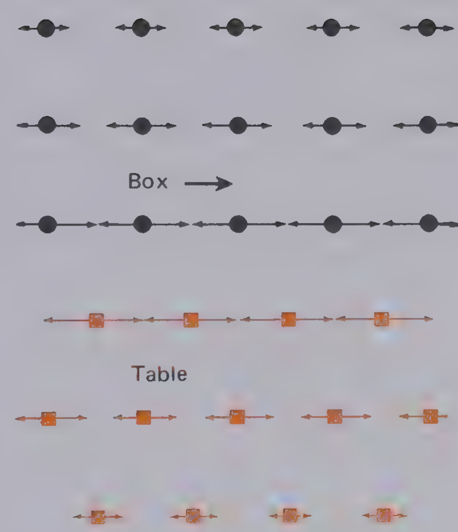
simplification is satisfactory to make our point. The "box molecules" exert attractive forces on each other as do the molecules in the table. The molecules of the box also exert small attractive forces on those of the table.

As the box is pushed across the table, these forces pull each type of molecule slightly away from the region it was in before. The forces are not large enough to pull either molecule completely away from their old location and therefore, each table or box molecule soon snaps back to its original region of vibration. But they vibrate faster than before when they return.

The work needed to pull them apart in the first place was supplied by the external agent that was pushing the box. Some of this input energy is, of course, present as kinetic energy of the entire box, but some has gone into the extra vibration of molecules in each case. It is this extra kinetic energy of molecules that we call heat energy!

As molecules near the region of contact oscillate with this extra energy, they of course collide with nearby molecules, transferring some of their kinetic energy to them. Thus, the "heat energy" that was generated at the contact points is distributed throughout each body. This is the process called *heat conduction*. Of course, some of this vibrational energy will be transmitted, via collisions, to the molecules in the air. It is in this way that any sound that might be heard as the box moves along the table, is produced.

Practically all interactions between bodies involve the production of some non-mechanical forms of energy such as heat or sound, because nearly always the force of friction is involved in interactions. Exceptions can be found when sub-atomic particles interact.



The result of holding and snapping free. The molecules vibrate most rapidly at the surface and this vibration goes from layer to layer, forming heat conduction.

*Q24 In what sense could heat and sound energy be thought of as mechanical energy? Why are they not usually regarded as such?

See also Problems 11.19 and 11.20 on page 44.

11.10 Heat as a Form of Energy

The story of our current understanding of the phenomenon of heat provides another example of the evolution of scientific ideas. Much of the following is taken from an excellent book on physics called *Physics for the Enquiring Mind* written by Professor Eric Rogers of Princeton University.

Heat as a Form of Energy

Lucretius (80 BC), describing the views of Greek philosophers several centuries earlier, wrote:

> No rest is allowed the elemental-atoms moving in space. Driven by perpetual and diverse motion, some, when they collide, leap far apart; and others are thrust but a short way from the blow. Those which when driven closer together rebound only a short way and are caught by their own entangling shapes, these form the substances of strong rock and rigid iron. Others leap far apart, with great spaces between; these supply for us thin air . . .

The speculations of the Greek Atomists seem to have remained forgotten or out-of-favour for many centuries. Ideas about atoms were revived in Galileo's time, and Newton later speculated that heat might be an atomic motion. Philosophers a century later had grandiose schemes for applying Newton's powerful mechanics to atoms, so that, given the positions and motions of all atoms they then could predict the whole course of the future. But the atomic picture was still only intelligent speculation and the association between heat and "atomic" motion a vague one.

Caloric

The idea of heat itself was none too clear for a long time after Newton. About 1750 Joseph Black made the clear distinction between *quantity of heat* and *temperature*. He measured heat by heating water or by applying heat to melting ice. In the latter case no thermometer was needed; the heat was measured by the mass of ice melted. He defined the useful quantity that we now call *specific heat* and in general built up a concept of heat as a definite "fluid" that moves without loss from hot things to cold. Even if heat seemed to disappear when things melted or evaporated, it was hidden as "latent heat" which could be recovered on reversing the change.

This fluid was soon named *caloric*. Heating a thing meant filling the spaces between atoms to a higher pressure of caloric. Specific heat was a measure of the amount of space between atoms to hold caloric. Water with its big specific heat had plenty of room between its atoms. Lead with a small specific heat must have very small spaces for caloric; a little caloric would suffice to fill the spaces to a high temperature. By 1800, the caloric theory was firmly installed in favour, with what seemed a good experimental basis.

It made experiments on heating and cooling, and melting and boiling, comfortable to think about. It accounted for such things as expansion on heating (the caloric nudged the atoms further apart), and it easily explained heating of matter by friction. When a sailor slides down a rope he squeezes caloric out of the rope, the calorists said. One could almost picture the man's hands wringing the heat out from between the rope's atoms like water out of a wet sponge. Why did not the caloric rush back in after the sailor let go? "Well the process is this," the explanation ran, "the friction squeezes the rope, making less room for caloric in it. So the caloric is pushed out and burns the man's hands. The change is permanent; the rope is left with less room for caloric in it." Less room for caloric? But in that case the squeezed rope must be left with a smaller specific heat. This could provide a crucial test of the caloric view. Experiments showed no change in specific heat; yet many calorists clung to their belief—as scientists will to theirs today. They probably excused any doubts about specific heat by saying that only a tiny fraction of the total caloric is squeezed out: the change in specific heat would be very small.

A New Suggestion for Heat

While Black and the calorists clarified and improved the measurements of heat, others were suggesting, with increased assurance, that heat is energy of molecular motion.

> Heat is a very brisk agitation of the insensible parts of the object, . . . what in our sensation is heat, in the object is nothing but motion.
>
> John Locke, 1796

> . . . heat is the vis viva resulting from the insensible movements of the molecules of a body.
>
> Lavoisier and Laplace, 1780

By 1800, the growing use of newly invented steam engines and the new understanding of the chemistry of burning gave engineers and natural philosophers (chemists and physicists) a common interest in the nature of heat. Lavoisier and Laplace suggested that animals and men "burn" their food with oxygen to form water and carbon dioxide, gaining just as much heat as if the same food were burned in a small stove and used to heat water. They argued that measurements of either oxygen used up or carbon dioxide breathed out would show how much food had been "burned". They were suggesting the idea of chemical energy that could be released in burning. In 1779, Crawford kept a guinea pig in an insulated box and measured its heat output for a measured consumption of oxygen. He then replaced the guinea pig by a tiny coal fire, burning carbon. For the same consumption of oxygen, the carbon fire produced about the same amount of heat. Burning wax gave a similar result. His actual results, given as temperature-rise of a standard mass of water were:

Guinea pig	1.73F°
Wax	2.0 F°
Carbon	1.93F°

These figures hardly proved the case, but they were suggestive. Such experiments are indeed difficult, but they have since been carried out with great precision on animals and on men. Their results show that the heat developed by the animal agrees with the heat got by burning the same food to within a fraction of one percent.

Modern Values of Chemical Energy Content of Some Foods

(1 kilocalorie = 240 joules)

Food	Energy Content kilocalories per kg
Beef (hamburger)	3880
Whole milk	730
Sweet corn	910
White rice	1270
Potatoes (boiled, peeled)	890
Wheat (whole meal)	770

Adapted from U.S. Dept. Agric., Agriculture Handbook No. 8, June 1950.

Evidence: Rumford

At the end of the eighteenth century, Count Rumford produced the first strong experimental evidence that heat is not a conserved fluid but

something that can be manufactured in unlimited amounts at the expense of mechanical energy.

Rumford, whose original name was Benjamin Thompson, was a remarkable man. Born in New England he chose the side of the Loyalists in the Revolution and had to leave for England under some pressure. He proved to be a magnificent organizer with great ability and strong interest in scientific experimenting. He also showed skill in gaining popularity and honour. He was knighted for his services; then he set out to travel across Europe. In Bavaria he made so favourable an impression as an organizer that he was given the post of war minister and asked to reorganize the army. While serving in this capacity in a Bavarian arsenal, Rumford investigated the heat developed when brass cannons were being bored. A blunt borer removed hardly any metal, but produced a huge supply of heat. Rumford boiled kettles on the cannon while horses drove a very blunt borer. He concluded that the supply of heat was inexhaustible, depending only on the horse continuing to work. He was progressing towards the idea of heat as a form of energy.

Proof: Joule

By 1840 the caloric theory was under severe attack, though still a popular tradition generally held by scientists. The time was ripe for the new belief that heat can be manufactured or destroyed in exchange with mechanical energy; but the idea was not clearly formulated, even the name "energy" was new. Precise experiments, and a wide variety of them, were needed to establish heat as a form of energy. These came with a rush in the early 1840's.

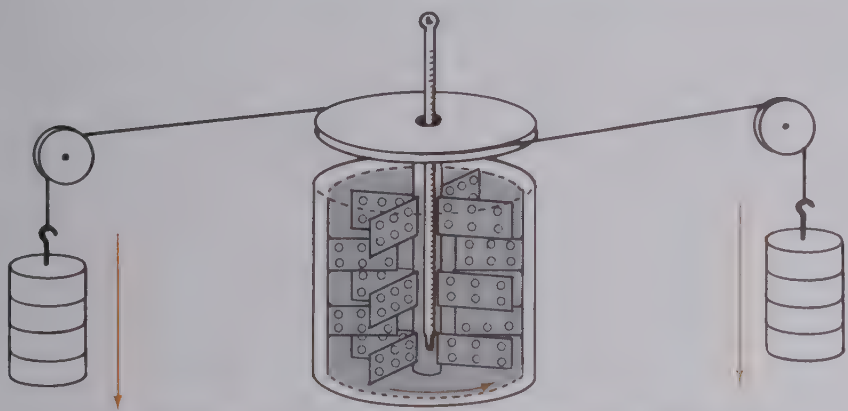
To appreciate our firm belief in Conservation of Energy, you should treat these experiments as witnesses, testifying in court for the new theory. To carry a case against a strong opponent, many witnesses are needed. They must each tell much the same story, and they are more convincing if they are unconnected, not all from the same family. If heat is a form of energy, interchangeable with *PE* and *KE*, every experiment which makes such an interchange must show the same rate of exchange between heat and mechanical energy. Experiment after experiment was done to produce heat at the expense of some mechanical energy. Loss of mechanical energy was measured by force-distance and gain of heat by mass-of-water times temperature rise times specific heat. Each time the question was asked, "Does each unit of *PE* lost produce the same amount of heat?" Or, "Does the same number of newton-metres of *PE* disappear for every calorie that appears, whatever the material or method?" If the same conversion-rate holds in all transactions—with heat and/or chemical energy and/or electrical energy—we can claim a general scheme of conservation.

Many of the experiments were done by J. P. Joule, the Manchester brewer, an amateur scientist who put his heart into proving his conviction that heat is a form of energy. Joule developed experimental proofs with great enthusiasm and incredible skill. The quantitative relation between heat energy, expressed in kilocalories, and mechanical energy, expressed in joules, is

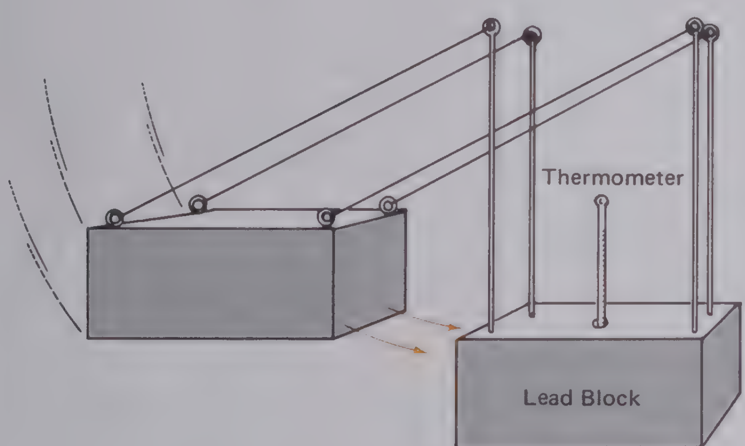
$$1 \text{ kilocalorie} = 4184 \text{ joules.}$$

He made his argument convincing both by the variety and by the precision of his measurements.

These diagrams illustrate Joule's experimental methods.



Representation of Joule's experiment which establishes the connection between heat and potential energy. Doubling the masses falling doubles the loss of potential energy and doubles the amount of heat produced in the water.



Joule's proof of the relation between Kinetic Energy and Heat. A measurable amount of *KE* was lost on each collision. Doubling or tripling the Kinetic Energy lost produced a corresponding increase in the rise in temperature.

Q25 What was the caloric supposed to be?

*Q26 In what ways does our modern concept of heat differ from the caloric viewpoint?

11.11 The Law of Conservation of Energy

The original concept of the *vis viva*, the mv^2 quantity that Huygens in 1668 claimed was conserved in perfectly elastic collisions was the stimulant for a very far reaching set of concepts. The use of the word "energy" to denote the quantity of work that a system can do was begun by Thomas Young in 1807. We have see that man first described the forms which this energy can take as either potential or kinetic energy. It took 180 years from Liebniz' introduction of the possibility of conservation of vis viva until Joule showed convincingly that heat was also just a form of energy. Soon after this important breakthrough, it was found that many phenomena - sound, electricity, magnetism, light, chemical reactions, all could be described in terms of energy, that all forms of energy could be transformed into one another, and that the total amount of energy in the universe was constant.

The newly developing science of electricity and magnetism, for example, showed that electricity was related to a number of other phenomena. Volta's invention of the battery in 1800 showed that electricity could be produced in chemical reactions. It was soon found that electric currents could produce heat and light. Oersted discovered in 1820 that an electric current produces magnetic effects. In 1822, Seebeck discovered that if heat is applied to the junction between two metals, an electric current is set up, and in 1831 Faraday discovered electromagnetic induction: a magnet moved near a coil of wire produced an electric current in the wire.

To some speculative minds these discoveries indicated a unity of the phenomena of nature and suggested that they were all the result of the same basic "force". This vague, imprecisely formulated idea bore fruit in the form of the law of conservation of energy: all the phenomena of nature are examples of the transformation from one form to another, without change of quantity, of the same basic thing: energy. The chart on page 40 shows the rate of energy input to the earth from the sun, and the rate at which we are using energy sources and energy reserves on earth.

Let us turn attention to the earth's primary source of energy, the sun. As we have seen, the ancients recognized the importance of the sun and deified and worshipped it as an object of great influence. With the development of science, man's dependence on the sun became perhaps even more obvious. But his knowledge of it was now rather more sophisticated. Man learned to view the sun as no different from the thousands of other stars in the sky. He was able to describe its importance to life in terms of the rate of its energy output, and link this energy to all processes involving both living and inert matter. The sun appeared as no less awesome perhaps than it was to the ancients, but the sense of wonder was on a different plane. How could the sun continue to pump out energy at the staggering rate that it did? Calculations based on the assumption that the sun was a burning mass of some fossil fuel such as coal or oil revealed that these sources could not provide energy at the rate the sun did for

as long as the sun had. Could it be that some process other than simple combustion was responsible for the tremendous energy output? Theories proposed by Mayer and Helmholtz in the mid-1800's suggested that the sun was slowly collapsing and that the gravitational potential energy lost with collapse was being converted into the output energy, or that the output energy was provided as the sun turned kinetic energy from comets and meteors into heat energy. But calculations showed both of these theories to be insupportable. The first required a rate of shrinkage of the volume of the sun that was not observed, and there was insufficient meteoric material near the sun to support the second hypothesis. The newly enunciated principle of total energy conservation that had evolved in the nineteenth century was faced with a stiff test. Was it reasonable to hold that the principle of energy conservation is a universal one? Did it extend to the stars? Could the physical processes that occur in the stars be duplicated on earth? More fundamentally, what attitude should one adopt when faced with a problem such as this, where no known energy transformation process could account for the observed energy outflow satisfactorily?

Newton's formulation of the law of gravitation and the range of celestial objects that seemed to behave in a way consistent with this law suggested that earth-bound physical studies could reveal information applicable to the stars. The principle of energy conservation linked many fields of science study on earth previously thought to be unrelated. Perhaps the energy concept linked earth and sky as well. Considerations such as these suggested that all processes in the Universe were indeed subject to the law of conservation of energy. If the solar processes could not be accounted for by starting with any known energy source, then there must be some new type of energy transformation taking place in the sun, some mechanism capable of unlocking in some unknown way, tremendous amounts of energy from storage, and yet behaving within the confines of the law of conservation of energy.

When the mechanism and storage place for the sun's energy were uncovered in the 1940's, there were some surprises. Energy was not being created from nothing, but, as Einstein had predicted in 1905, yet another part of the physical world was revealed to be linked with energy! The energy output of the sun could be accounted for successfully by a process that was called nuclear fusion, in which a small quantity of mass "disappeared" and a large quantity of energy "appeared" in its place! But one cannot use this word "disappeared" and still maintain the principle of conservation of mass. Nor can the "appearance" of energy be consistent with the principle of conservation of energy. These problems were resolved by understanding mass as just another form of energy! The equivalence of mass and energy has broadened the conservation of energy principle still further. As you will learn in Unit 6, in interactions involving atomic nuclei, mass often becomes transformed into energy, and energy into mass. In all such processes it is the *combination* of mass and energy that is conserved.

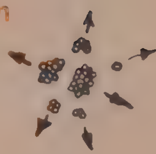
Einstein expressed the equivalence of mass and energy with the equation

$$E = mc^2$$

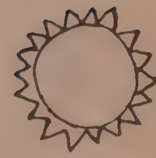
(c is a constant)

Energy Conservation on Earth

Nuclear reactions inside the earth produce energy at a rate of 3×10^{17}W



The nuclear reactions in the sun produce energy at a rate of 4×10^{26}W



The earth receives about 8×10^{17} W from the sun, of which 5/8 is immediately reflected - mostly by clouds and the oceans.

Of that part of the solar energy which is not reflected,,..

...7×10^{16}W heats dry land

....3×10^{16}W heats the air, producing winds

...2×10^{17}W evaporates water

...4×10^{14}W is used by marine plants for photosynthesis

...5×10^{13}W is used by land plants for photosynthesis

Most of the energy given to water is given up again when the water condenses to clouds and rain; but every second about 10^{15} Joules remains as gravitational potential energy of the fallen rain.

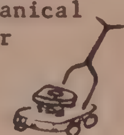
Some of this energy is used to produce 3×10^{10}W of hydro-electric power

Ancient green plants have decayed and left a store of about 5×10^{22} Joules in the form of oil, gas, and coal. This store is being used at a rate of 4×10^{13}W.

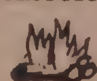
Present-day green plants are being used as food for man and animals, providing energy at a rate of 3×10^{11}W

10^{12}W is used in generating 3×10^{11}W of electrical power

10^{13}W is used in combustion engines. About 3/4 of this is wasted as heat; less than 3×10^{12}W appears as mechanical power



3×10^{13}W is used for heating; this is equally divided between industrial and domestic uses.

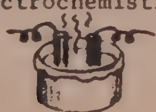


Direct use as raw materials for plastics and chemicals accounts for 10^{12}W

Controlled nuclear reactions produce 3×10^{9}W in electrical power

3×10^{11}W

electrochemistry



light

communication

mechanical power

The principle of conservation of energy has been so successful and is now so firmly believed that most physicists find it almost inconceivable that any new phenomenon will be found that will disprove it. Whenever energy seems to appear or disappear in a system, without being accounted for by changes in known forms of energy, physicists naturally prefer to assume that some unknown kind of energy is involved, rather than accept the possibility that energy is not conserved.

Activity 11.6, *A Law You Can Trust.*

We believe this will probably always be the case: any apparent exceptions to the law of conservation of energy will sooner or later turn out to be understandable in a way which does not force us to give up the law. At most, they may force us to postulate new forms of energy so that the law will become even more generally applicable and powerful.

The French mathematician and philosopher Henri Poincaré expressed this idea in 1903 and in his book *Science and Hypothesis:*

Film Loop 11.1, *Conservation of Energy—The Pole Vault.*

> Since we cannot give a general definition of energy, the principle of conservation of energy signifies simply that there is something which remains constant. Indeed, no matter what new notions future experiences will give us of the world, we are sure in advance that there will be something which will remain constant and which we shall be able to call energy.

In closing, there is a point concerning the interaction between science and philosophy that arises from our discussion of the energy coming from the sun.

Man was faced with the perplexing problem of the origin of the sun's energy. Some saw this as a theological issue deserving a philosophical rather than a scientific answer. They saw the source of the sun's energy as being continuously created out of nothing by divine power. They even regarded the fact that the problem seemed to be one that science could not answer as offering some sort of proof of the existence of God. Similar views indeed have often been put forth by scientists. Newton, in Book III of the *Principia*, in discussing the planets and comets tells us:

> . . . beautiful system of the sun, planets, and comets, could only proceed from the counsel and dominion of an intelligent and powerful Being . . .

As we have seen earlier in the course, when science has eventually found plausible answers to questions which theology had previously dealt with, the scientific views have often met with stiff resistance. The Copernican theory, Galileo's astronomical work, Darwin's theory of organic evolution are other examples. Each time that the scientific answers were not in accord with the theological answers, or that phenomena could be accounted for by other than direct divine intervention, came as a shock. But surely the error here lies in an arbitrary prejudgement of what man can and cannot do. Many people seem to base their faith in God at least partly on the existence of questions about nature that man cannot answer. Others take an opposite course and tend to deify science itself. But the "truths" of science have not yet revealed any impressive ability to stand the test of time. To the contrary, the answers science offers have changed and

evolved throughout history. "Laws" that fit the data available in one period of time may have to be changed as new data becomes available. As one historian of science puts it:

> The secure basis for belief, as all great religious leaders have taught, is not to be found in the judgment of man's intellectual capacities or his limitations, and not in science's presumed powers or inadequacies; rather, it is to be found only in faith.

Q27 These questions can be answered using data in the chart on page 40.

a) What percentage of the sun's total energy output is actually received at the earth's surface? What happens to the rest?

b) What percentage of the energy received at the earth's surface is used to evaporate water?

c) Fossil fuel reserves are being used at a rate of 4×10^{13} watts. How long should the total reserves of 5×10^{22} joules last? (Express answer in years.)

*Q28 Choosing any two of the following, trace the chain of energy transformations from the sun to the final form of energy:

a) A pot of water is boiled on an electric stove.

b) An automobile accelerates from rest on a level road, climbs a hill at a constant speed, and comes to rest at a traffic light.

c) A windmill in Holland pumps water out of a flooded field.

*Q29 Write a statement of the law of conservation of energy.

Problems Chapter 11

Section A

11.1 A 10 N force is applied to a body in its direction of motion, and a 3 N frictional force acts opposite to its direction of motion. Calculate the work done by the applied force while the body moves 4 metres.

11.2 a) Express the power of a 350-horsepower car engine in units of kilowatts.
b) Determine the energy expended during one hour of operation when the engine is operating at its rated power.

11.3 How long would it take a crane-motor to lift a 1000-kilogram container 5 metres from the ground to a storage platform if its power is
a) 10 kilowatts
b) 20 kilowatts?

11.4 a) Calculate the work done by a 5.0-N force which moves a body 3.0 metres in 1) 2.0 seconds 2) 4.0 seconds
b) Calculate the power in each case.

11.5 a) An electron has a mass of 9.11×10^{-31} kilograms. If it moves across a television picture tube at a speed of 5.00×10^{5} metres per second, calculate its kinetic energy.
b) How many such electrons would transfer one joule of energy to the screen?

*11.6 When a gun is fired, the momentum of the gun is almost the same as the momentum of the bullet but in the opposite direction. Why is it much more dangerous to be hit by the bullet?

11.7 A 200-kilogram iceboat is supported by a smooth surface of a frozen lake. The wind exerts on the boat an average force of 100 newtons, while the boat moves 36 metres. Assume that frictional forces are negligible, and that the boat starts from rest. Find the speed after 36 metres by each of the following methods:
a) Use Newton's second law to find the acceleration of the boat. How long does it take to move 36 metres? How fast will it be moving then?
b) Find the final speed of the boat by equating the work done on it by the wind and the increase in its kinetic energy.
*c) What is the advantage in this problem of the energy approach of part b compared to the approach of part a)?

11.8 Foods are said to possess "chemical potential energy". In what sense can this stored energy be considered as energy due to the position of one body with respect to the other, that is, as potential energy?

11.9 A 20-kilogram bag of dry cement rests on steel girders of a building under construction. It is 30 metres above the ground and 5 metres above a worker sitting one floor below the bag. What is the gravitational potential energy of the cement bag
a) with respect to the ground level?
b) with respect to the worker 5 metres below the bag?
c) Explain how the potential energy of the bag is related to the concept of work.

11.10 a) It is estimated that 5×10^{8} kg of water flow over Niagara Falls each minute. The average height of the fall is 65 metres. What is the total amount of gravitational potential energy, measured with respect to the bottom of the fall, represented by the water flow during one minute?
b) How much power is represented by the water?

11.11 A pendulum bob of mass 2.0 kg is suspended from a hook by a string 0.80 metres long. The bob is pulled until the cord is horizontal and then is released. Assuming mechanical energy is conserved, calculate the maximum speed of the bob during its swing.

11.12 An archer exerts an average force of 100 N as he draws the arrow back .6 metre preparing to shoot.
a) What is the potential energy in the bow and arrow system just before the archer releases the arrow?
b) What will be the kinetic energy of the arrow in flight? State any assumptions you make.
c) If the arrow has a mass of 0.02 kg what would its maximum speed be?

11.13 A 0.5-kilogram stone is dropped by a boy in a tree fort 5.0 metres above the ground.
a) What is its potential energy with respect to the ground just before it has dropped?
b) Assuming mechanical energy is conserved, calculate the speed of the stone just before it hits the ground.
*c) Do you think the assumption that this is a conservative system is realistic? Why?
*d) Suppose a leaf fell to the ground from the same height up the tree. Would mechanical energy be conserved? Why?

11.14 Assume that a child slides down a frictionless playground slide. Upon what factors does his speed at the bottom depend? Why?

11.15 a) A 1.0-kg toy car on a friction free surface is accelerated horizontally at 3 metres per second per second. How much work is done while it moves 2 metres?
b) The same toy car is now accelerated vertically at 3 metres per second per second. How much work is done while it moves 2 metres?
*c) Comment on your answers to a) and b) from the point of view of changes in mechanical energy.

11.16 a) A 1.0-kg stone is thrown vertically upward at a speed of 20 m/s. Assuming that mechanical energy is conserved, what is the maximum height the stone will reach?
b) Assuming the system is a conservative one, how much kinetic energy will the stone have when it is 5 metres above the ground?

11.17 a) Two balls are thrown straight up in the air, ball *A* with twice as much energy as ball *B*. Compare their maximum heights.

b) Two balls are thrown straight up in the air, ball C with twice the speed of ball D. Compare their maximum heights.

11.18a) Sketch graphs of momentum versus velocity and kinetic energy versus velocity for a 2000-kilogram car moving at speeds between 1 and 100 kilometres per hour. (Compute values at intervals of 20 kilometres per hour.)

b) Assuming that the same stopping force is applied to the car by the brakes, compare the distances required to bring the car to a stop from speeds of 30, 60, and 90 kilometres per hour.

c) Under the same conditions as in b), compare the times required to bring the same automobile to a stop from these speeds.

*11.19 What makes a swinging pendulum finally come to rest? Where does the energy of the pendulum go?

*11.20 Discuss the following statement: All the chemical energy of the gasoline used in your family automobile is used only to heat up the car, the road, and the air.

*11.21 a) In this collision, there are a large number of velocities of A and B after the collision that would satisfy the condition that momentum be conserved. Apply the condition for conservation of momentum to derive an equation for possible values of v_A' in terms of v_B'.

b) There are also a large number of values of velocities for A and B after the collision that would satisfy the condition that kinetic energy be conserved. Apply the condition for conservation of kinetic energy to derive an equation for possible values of v_A' in terms of v_B'.

c) Values of v_A' and v_B' that satisfy the equations in parts a) and b) above have been plotted in the graph of Fig. 11.9. You may want to plot your own graphs and compare them to this one. This would be a means of checking your answers to a) and b).

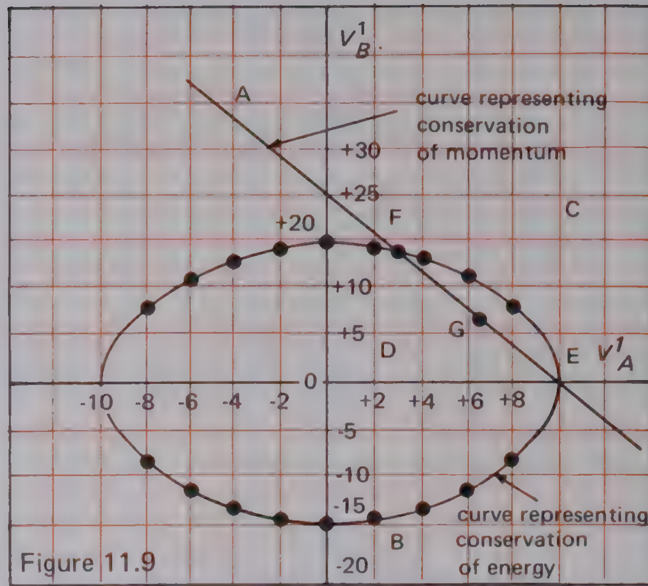


Figure 11.9

d) Part of the skill of scientists and engineers lies in being able to interpret the physical meaning of different regions in graphs of data such as this. Say as much as you can about the "curves" A and B, region C (all points outside the ellipse), region D (all points inside the ellipse), and points E, F, and G.

11.22 A 100-kg case must be loaded into a truck whose floor is 1.5 metres above the ground.

a) What force would be required to lift it directly up from the ground to the truck?

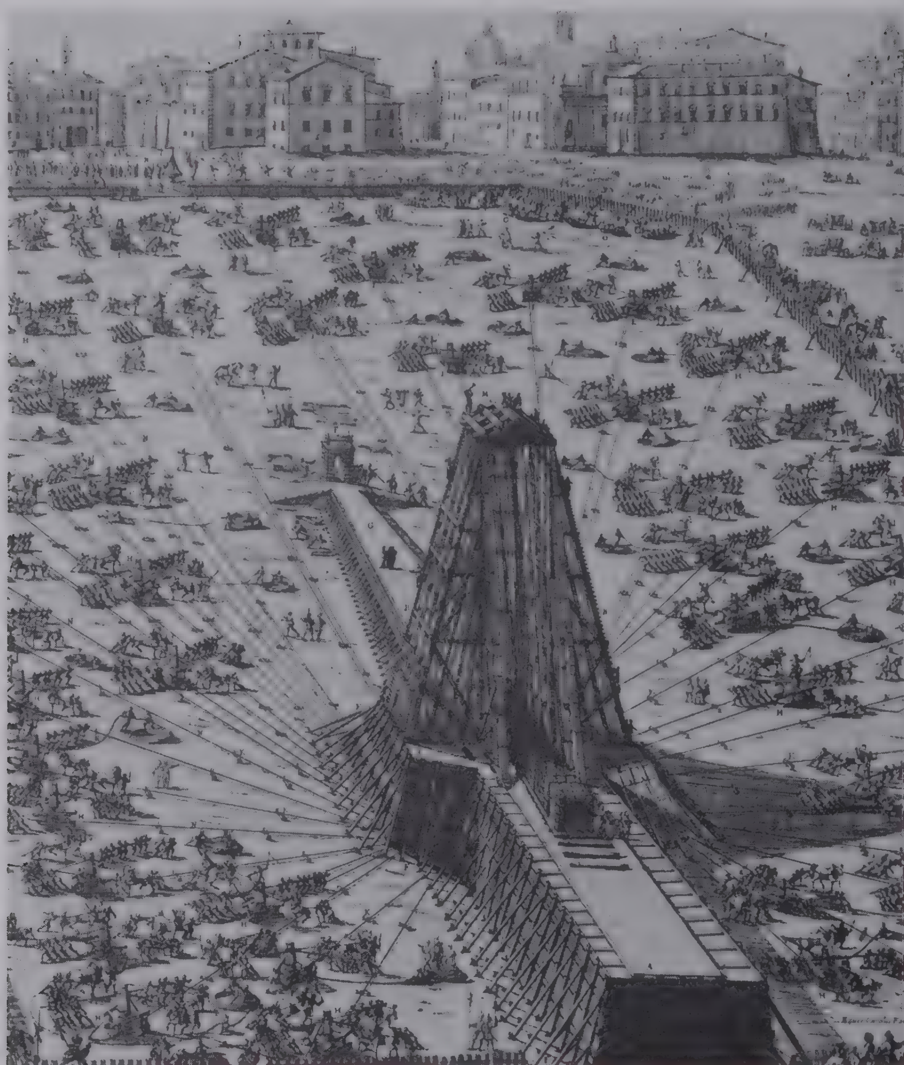
b) Calculate the work done in lifting the case directly into the truck.

c) The same work is done if the case is pushed up a ramp, providing friction can be reduced to a negligible value. The advantage gained is that the same job can be done with less force than that required by a direct lift. Calculate the force required if the ramp is 3.0 metres long.

d) If the force of friction cannot be made small, then a force of perhaps 700 newtons might be required to pull the case up the 3.0 metre ramp. i) Calculate the work done by the force in this circumstance. ii) How much of this would remain as potential energy of the case? iii) What happens to the rest of the energy?

Chapter 12 *The Energy Crisis*

A 310,000 kg obelisk is moved by muscle power.



The Energy Crisis

Chapter Twelve

"The Energy available to man limits what he can do and influences what he will do."

Man needs energy. His most basic need is in the form of the ten thousand joules of food energy which are considered essential for his daily survival. Although survival from starvation was man's only need for much of his existence on the earth, his requirements soon increased as his social structure became more complex. He wanted to build dwellings, towers, and monuments. He wanted to transport food, materials and people. These needs resulted in the construction and use of the many simple machines that form the basis for our modern technology. We shall consider some of these early inventions in the next section. The energy to operate these simple devices came mostly from man himself, although the taming of animals provided another readily available energy source.

In time man turned to other sources of energy. He first used the wind and flowing water. And then, following the invention of the steam engine, he turned to the fossil fuels in his attempt to satisfy the energy needs that would permit him to live in more comfort and to extend his influence. The fossil fuels have since become the world's primary source of energy for the generation of electricity. Now man is developing a technology based upon energy released from the nucleus of the atom. We are no longer using energy at the minimum existence level at ten thousand joules per person each day, but have increased our demand so that the average Canadian's daily energy demand is about one billion joules.

This figure represents our total energy requirement, not just our daily food consumption.

1 billion = 10^9

Recently society has begun to question this increased use of energy. We are concerned with the depletion of our energy sources and with the formation of the many pollutants that are products of our energy-hungry society. It is not enough for the physics student of the twentieth century to understand the terminology and formulae that form the scientist's view of

energy. It is hoped that this chapter will present you with a wider look at the evolution of man's search for sources and methods of using energy as well as some of the consequences.

12.1 Machines: How to Use Energy

Give me a fulcrum on which to rest and I will move the earth.
Archimedes

machine
— *mechane* (Greek)
— *machina* (Latin)
meaning an ingenious device.

In the previous chapter we became familiar with the scientist's description of energy. We defined terms, derived equations, and solved some simple problems. Reconsider a problem of this type.

Calculate the energy used in lifting a 500-kg mass to a height of 0.5 metres.

Energy used = work done
= force to lift object × height
= 5000 N × 0.5 m
= 2500 joules

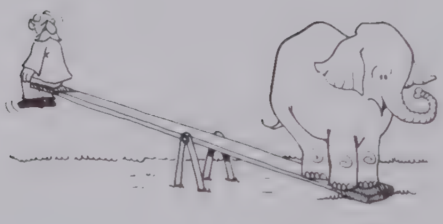
Do you have enough energy to lift a 500-kg object to a height of 0.5 metres?

The mathematical calculations for a flight to the moon were carried out in the eighteenth century. But it was only with recent developments in technology that the mission could be carried out.

Since the required 2500 joules of energy is approximately equivalent to the energy you would use in climbing stairs to a height of about 5 metres, you certainly would have enough energy to carry out the task. However, you probably would have great difficulty in doing it. Not because you don't have enough energy, but because you cannot lift a 500-kg object easily. It is very heavy. The previous chapter discussed the mathematical calculation of energy to perform certain tasks. However, this did not mean that the tasks could be carried out easily.

Let us now consider some devices that would permit us to actually carry out some of the tasks we discussed theoretically in the last chapter. The five fundamental machines we shall consider were known by the ancient Greeks and listed in the writings of Archimedes. They are the lever, the wheel and axle, the pulley, the inclined plane and wedge, and the screw.

a) *The Lever*


Experiment 12.1, *Levers.*

From a few simple experiments using a lever, it becomes obvious that you can lift heavy objects with ease. The factor that determines the force necessary to lift an object is the position of the fulcrum. The closer the fulcrum is placed to the load the less force is required to lift it.

The relationship between force, load, and fulcrum position is called the *law of the lever* and is written mathematically as the following equation:

$$\text{Force} \times \text{Force Arm} = \text{Load} \times \text{Load Arm}.$$

$$F \times FA = L \times LA.$$

We can use this equation to calculate the position at which a force of 500 N must be applied to lift a 5000 N weight located 1 metre from the fulcrum.

$$FA = \frac{L \times LA}{F} = \frac{5000 \text{ N} \times 1 \text{ m}}{500 \text{ N}} = 10 \text{ m}.$$

This lever is illustrated in the sketch below (Fig. 12.1). Using this lever it is possible to lift a 5000 N weight by using a force of only 500 N.

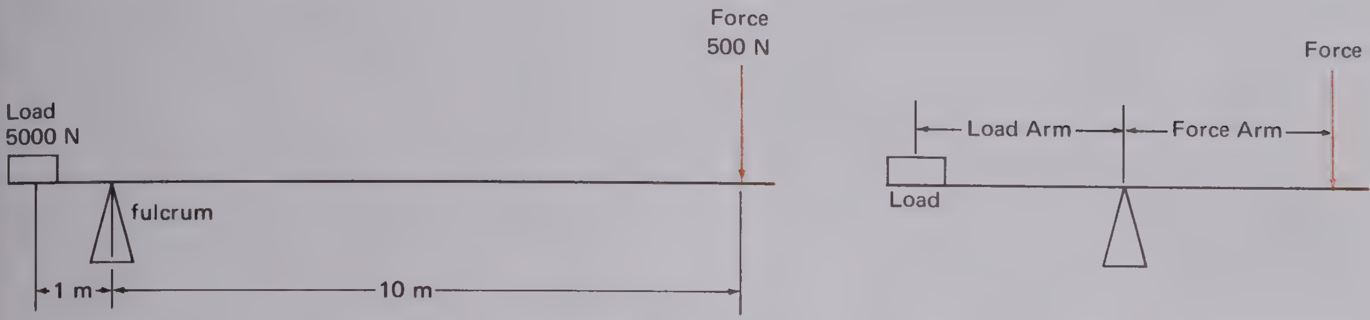


Fig. 12.1

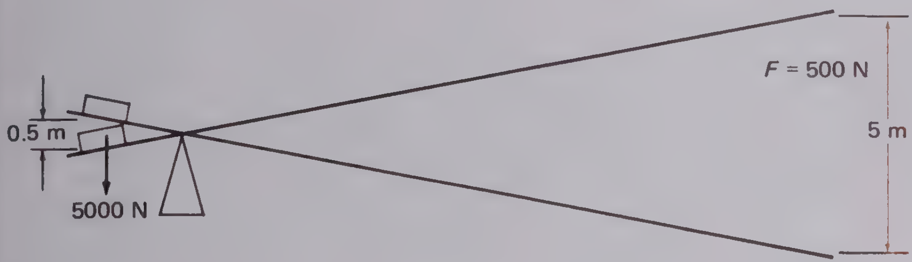


Fig. 12.2

But, by lifting a 5000 N weight using only a 500 N force are we not violating one of nature's basic laws? It seems that we are getting something for nothing. Is this not a violation of the law of conservation of energy? Consider Fig. 12.2 which shows the positions of the lever before and after the object has been lifted. Notice that in order to lift the object 0.5 metres, the force moved through a displacement of 5 metres. Comparing the work done in lifting the object (energy input) to the gain in the object's energy, we find the following:

$$\begin{aligned} \text{Energy input (work done)} &= F \times d \\ &= 500 \text{ N} \times 5 \text{ m} \\ &= 2500 \text{ joules.} \end{aligned}$$

$$\begin{aligned} \text{Gain in object's energy} &= \text{weight} \times \text{height} \\ &= 5000 \text{ N} \times 0.5 \text{ m} \\ &= 2500 \text{ joules.} \end{aligned}$$

The law of conservation of energy was not violated. We did not get more energy out than we put in.

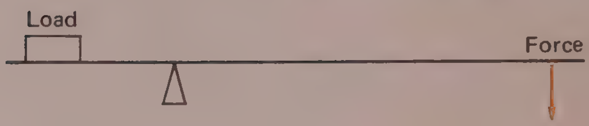
The advantage of using the lever and other simple machines is not that they permit us to get out more energy than we put into a task but, they do provide us with a means of increasing the force that we can bring to bear on a certain task. This

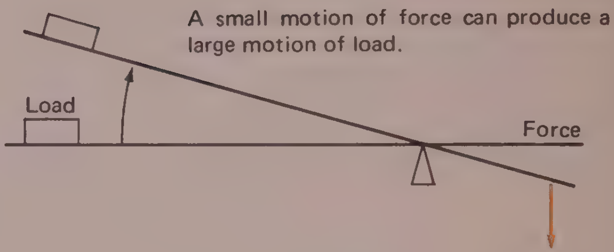
Activity 12.4, *A Car Jack.*

First Class Lever

The type of lever which we have discussed in the text with the fulcrum located between the load and the force is called a first class lever. Usually it is used with the fulcrum located near the load to give the greatest mechanical advantage. However, when the load is not too great, the fulcrum is sometimes placed near the force. In this case although a force greater than the load is required to lift the object, there is a gain in the displacement of the load.

A small force lifts a heavy object.

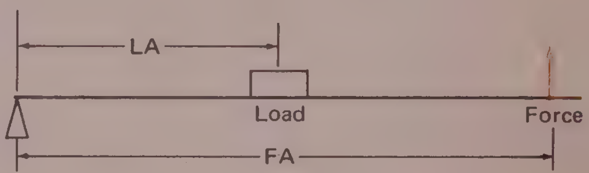




Second Class Lever

Different classes of levers are produced by changing the position of the fulcrum relative to the force and load. When the load is placed between the force and fulcrum the resulting lever is called a second class lever.

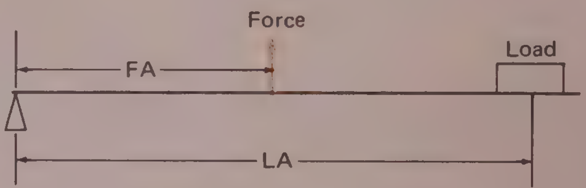
In this lever the mechanical advantage is always greater than 1 because the force arm is always longer than the load arm.



Third Class Lever

A third class lever is constructed by placing the force between the fulcrum and the load.

To operate, this lever always requires a force greater than the load. However, a small displacement of the force can produce a large displacement of the load. There are many examples of the lever in animal physiology where its function is to magnify displacement.



increase in the force, however, requires us to exert the force over a greater distance than if we had done the task directly. The ratio of the force acting on the load to the force applied (effort) is called the mechanical advantage.

To lift a 5000-N load to a height of 0.5 m

	Directly	Using Lever
Force	5000 N	500 N
Displacement of Force	0.5 m	5 m
Work Done	2500 j	2500 j

For the lever in our example, the mechanical advantage $= \frac{load}{effort} = \frac{5000\ \text{N}}{500\ \text{N}} = 10.$

In practice we find that the useful energy output is less than the energy input. Even in a machine as simple as the lever, there is some energy input that does not get transferred to lifting the object. This energy is used up in bending the beam or in heat loss due to friction between the beam and the fulcrum. The more complex the machine the greater is this transfer of energy into a form that is not useful.

In practice

$$MA = \frac{\text{load}}{\text{effort}}$$

which ideally equals $\frac{FA}{LA}$ from the law of the lever.

Q1 Where on a seesaw must a person with a mass of 30 kg sit in order to balance a person weighing 50 kg who is 2.5 m from the fulcrum?

Q2 In using a car jack, a person discovered that an effort of 100 newtons produced a lifting force of 1200 newtons.

a) What is the mechanical advantage of the jack?

b) If the length of the handle (force arm) is 50 cm how far is the load located from the fulcrum?

c) If each stroke lifts the car 1 cm, how far does the end of the handle move downward each stroke?

Q3 The force in a human arm is applied approximately 2 cm from the elbow and the hand is 24 cm from the elbow. What force must be exerted to lift a 1-kg object held in the hand?

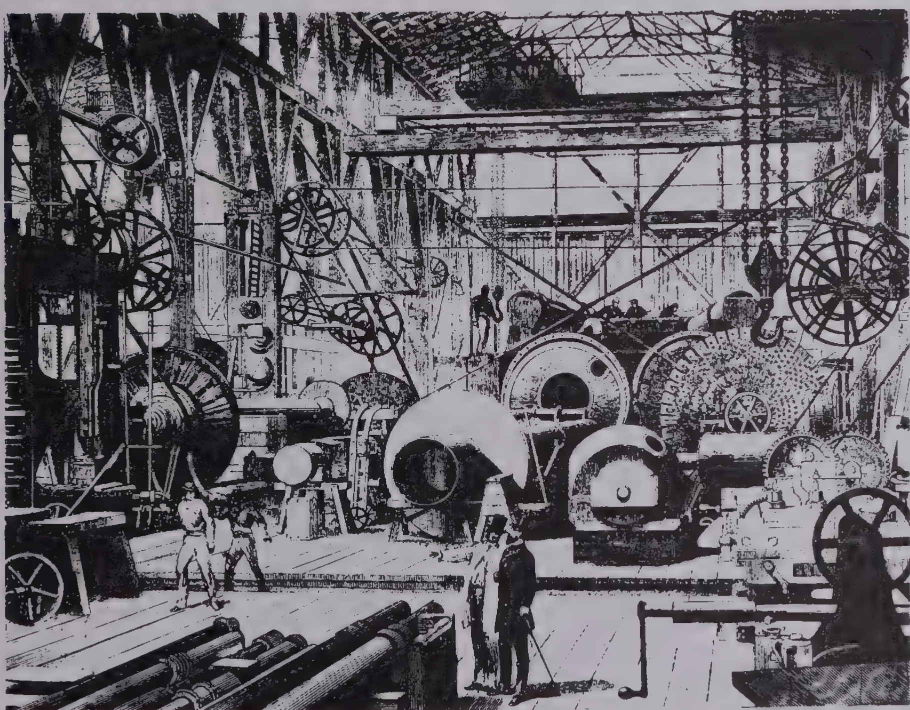


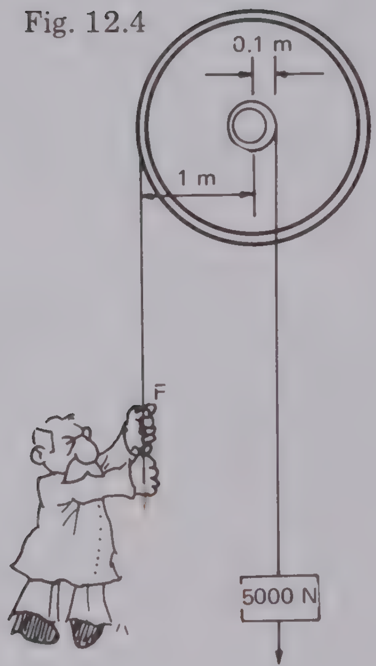
Fig. 12.3

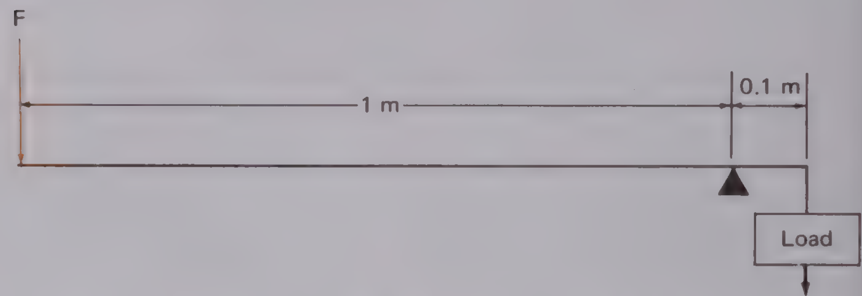
b) *The Wheel and Axle*

Before the development of electrical technology the most common method of energy transfer from place to place within a factory was by using belts, wheels, and axles. You can get some appreciation for the complexity of this method of energy transfer by examing the engraving (Fig. 12.3).

By using various wheel and axle arrangements, the principles of the lever may be applied to a rotational machine. Consider again the problem of lifting the 5000 N weight. An arrangement using the wheel and axle is shown in Fig. 12.4. The similarity between the wheel and axle and the lever is also illustrated. Note that the axle acts as the fulcrum.

Fig. 12.4





The force required to lift the object using the wheel and axle illustrated in the sketch may be calculated as follows:

$$F = \frac{L \times LA}{FA} = \frac{5000\ \text{N} \times 0.1\ \text{m}}{1\ \text{m}} = 500\ \text{N}.$$

The ideal mechanical advantage of this machine is

$$MA = \frac{L}{F} = \frac{5000\ \text{N}}{500\ \text{N}} = 10.$$

However, note that again we are gaining force by moving through a greater displacement. In order to rotate the wheel once we must draw in a length of rope equal to the circumference of the wheel.

Circumference $= 2\pi R = 2\pi(1)$ metres

Thus the gain in potential energy of the load for one rotation:

$$\begin{aligned}\text{Force to lift} \times \text{height} &= 5000\ \text{N} \times 2\pi(0.1)\ \text{m}\\ &= 1000\pi\ \text{joules}\\ &\approx 3000\ \text{joules.}\end{aligned}$$

The work done in lifting the object by one rotation of the wheel

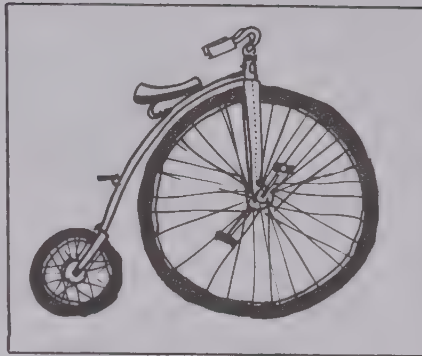
$$\begin{aligned}&= F \times d = 500\text{N} \times 2\pi\ (1)\ \text{m}\\ &= 1000\ \pi\ \text{joules}\\ &\approx 3000\ \text{joules.}\end{aligned}$$

Again we observe the law of conservation of energy holds true.

The ten-speed bicycle gear described on page 54 is an example of a contemporary adaption of this ancient device.

Q4 If a force of 50 N is applied to turn a steering wheel of radius 30 cm, what force is transmitted to the steering mechanism? (Diameter of steering axle = 2 cm.)

Q5 The bicycle in the margin was invented over one hundred years ago and was called the penny-farthing. (The ratio of the sizes of these two coins was similar to the ratio in the wheel sizes.) The pedal arm was 15 cm long and the radius of the large wheel was 75 cm. What is the mechanical advantage of this wheel and axle arrangement?

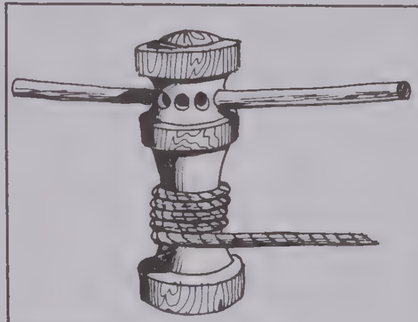


c) *The Pulley*

On the morning of April 30, 1586 more than 500 men and 74 horses were assembled in the piazza of St. Peter's in Rome. They awaited a trumpet signal that would initiate the moving of the 310,000-kg obelisk over a distance of 250 metres by muscle power. Although the earlier shifts of this obelisk were more impressive, the ancient Egyptians had moved it from the quarries at Assuan 900 km to Heliopolis, and the Romans brought it to Rome, we are provided with detailed information and drawings only for this latest move. In addition to the lever and the capstan, the chief engineer Domenico Fontana, also used another simple machine, the pulley.

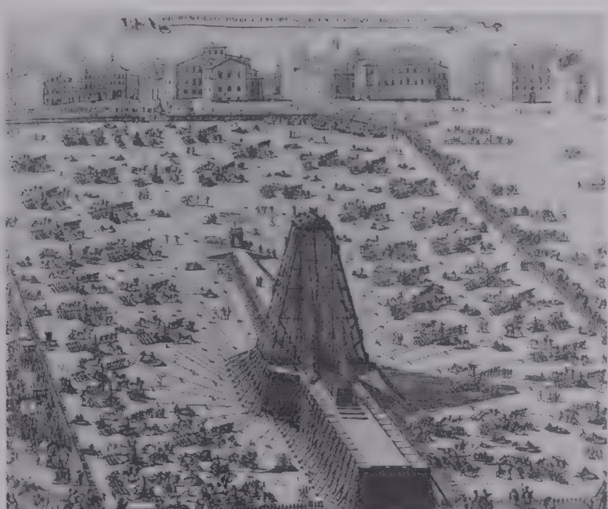
The Vatican Obelisk	
Height	25.2 metres
Base	2.8 metres square
Top	1.8 metres square
Mass	306,550 kg (≈ 340 tons)

Fontana, starting with the knowledge that each horse could pull with a force of about 45 kg, calculated his manpower and horsepower needs. Four horses pulling a capstan having a mechanical advantage of 9 would produce a force of 1620 kg at each capstan. This was increased by a pulley system to 6480 kg. He used 40 such systems to provide most of the force to lift the obelisk. The remaining force was provided by five large wooden levers. The account of this and other moves of the obelisks are told in the book *Moving the Obelisks* by Bern Dibner which would make enjoyable reading for anyone who has used a pulley to pull out a stump or raise a heavy load.



A capstan

Bern Dibner, *Moving the Obelisks*. M.I.T. Press, 1970.



THE "TEN-SPEED" RACER: A Recent Adaption of the Wheel and Axle

The following specifications and calculations are for the Citation-Deluxe ten-speed racer manufactured by CCM.

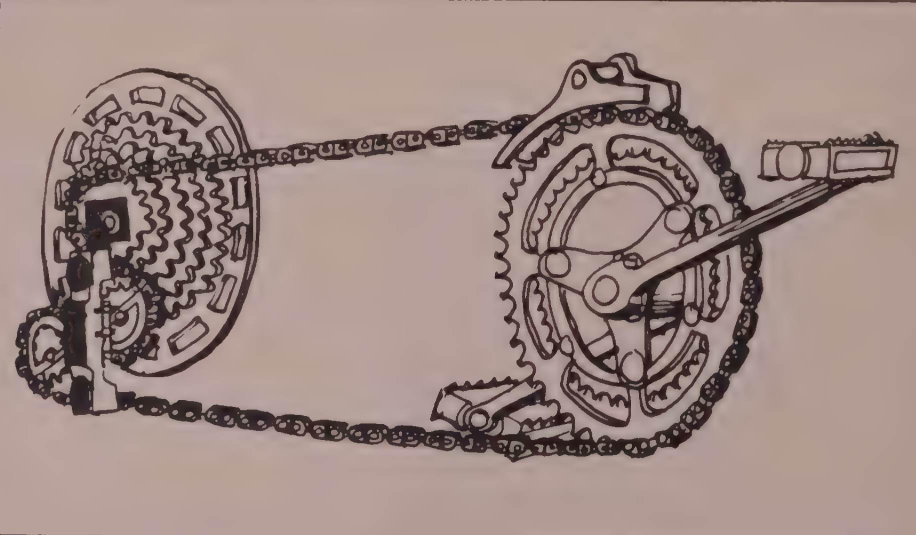
Specifications

Frame and Forks	— lightweight Reynolds 531 plain gauge frame tubes chrome plated tips
Rims	— 69 cm × 3.2 cm alloy
Tires	— 69 cm × 3.2 cm amber wall
Derailleurs	— simplex "Prestige" front and rear
Brakes	— light alloy centre pull—rubber covered, hooded levers
Weight	— 11-12 kg
Gear Ratio	— 96.0/114/124/139/146/158/174/196/205/252
Length of Pedal Arm	— 17.1 cm
Saddle	— all leather competition style
Price	— $150.00 (approx.)

Description of Sprockets:

Rear Wheel					
No. of teeth	14	17	20	24	28
Diameter (cm)	5.70	6.50	8.15	9.70	12.38

Chain Wheels		
No. of teeth	40	51
Diameter (cm)	16.18	21.00



Using these specifications, we can determine the range of possible speeds offered by this bike. We shall make calculations for its operation using the largest chain wheel sprocket (51 teeth) and the smallest rear wheel sprocket (14 teeth). It is more convenient to use the number of teeth than the sprocket diameter in our calculations.

Each time the pedal makes one revolution the rear wheel makes $51/14 = 3.65$ revolutions. During these revolutions of the rear wheel the bike would travel a distance equal to $3.65 \times \pi \times$ diameter of rear wheel $=$ $3.65 \times \pi \times 69$ cm $= 252\pi$cm.

Note: (The number 252 is called the *gear ratio*. The gear ratio $\times\ \pi$ is equal to the distance the bike travels in cm for each revolution of the pedal arm.)

If the pedal were rotating at the leisurely rate of 1 revolution per second, the bicycle would be travelling at $252\ \pi$ cm/s $=$ 7.9 m/s. The range of the speeds for the various gear ratios is given below for a pedal rate of 1 revolution/second.

Speeds (m/s) 3.16, 3.66, 4.05, 4.51, 4.70, 5.20, 5.60, 6.35, 6.65, 7.9

The range of these speeds is from 11.4 to 28.5 km/hr.

The mechanical advantage is lower at high gear ratios which are used for downhill and tailwind pedalling. The lower gear ratios provide a higher mechanical advantage for hill climbing. By choosing gears correctly, the cyclist may maintain his pedal rate for a variety of road conditions.

Data courtesy of CCM

For further information see: "Bicycle Technology", by S. S. Wilson in the March 1973 *Scientific American.*

Two pulley arrangements are shown in Fig. 12.5 below. In diagram a) the only advantage of using the pulley is that it changes the downward force on the rope to an upward force on the load.

Experiment 12.2, *Pulleys.*

The arrangement in b) has a mechanical advantage of two. The load is equally distributed between the support and the lifting force. The indication of load and force arms on the diagram permit a comparision with the lever.

A device consisting of one or more pulleys in a frame is called a *block*. When combined with a rope it is called a *block and tackle*

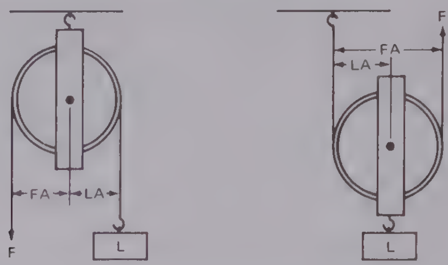


Fig. 12.5 The single fixed pulley in a) is basically a lever of the first class. How might you classify the single movable pulley in b)?

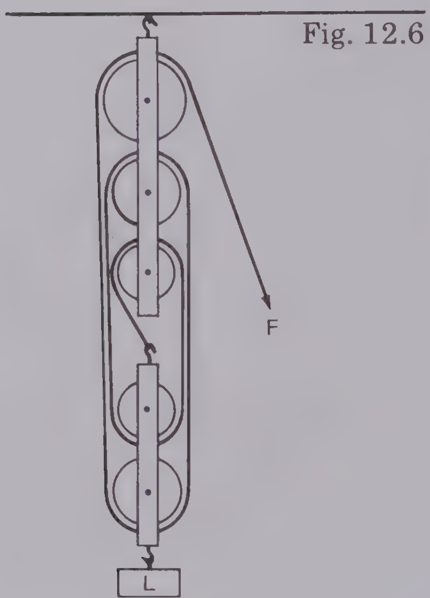


Fig. 12.6

The mechanical advantage of a pulley system increased with the use of a more complex arrangement. Fig. 12.6 shows a system with a mechanical advantage of five. One method of determining the mechanical advantage of a complex pulley system is to count the number of ropes *supporting the load*. In lifting this load to a height of 1 metre using a pulley system with a mechanical advantage of five, the operator must pull in 5 metres of rope.

Q6 For the pulley system shown in the marginal diagram (Fig. 12.6) determine:

a) the mechanical advantage,

b) the force that must be applied to lift a 500-kg load to a height of 3 metres,

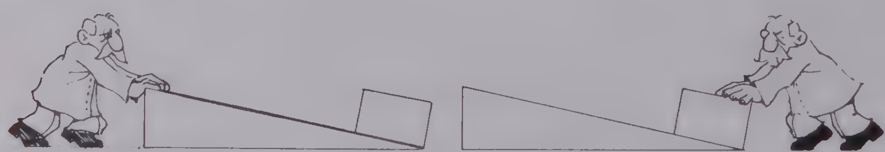
c) the work that must be done to lift a 500-kg load to a height of 3 metres.

d) How much rope must be pulled in to raise an object 3 metres?

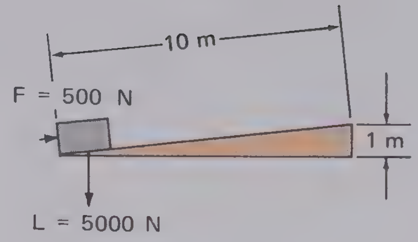
d) *The Inclined Plane and Wedge*

The fourth basic machine is one of the most evident in our everyday lives. It includes as examples sloped roads, ramps, knives, and even the "flying wedge" of the football field. The sketches below illustrate the difference in the use of the wedge and of the inclined plane. The wedge does its work by moving, whereas the inclined plane remains at rest while the load is moved over it.

Activity 12.3, *Pulley Puzzle.*



Both accomplish the same task of moving a load through a distance more easily than if the task were done directly. Consider the following example. It is observed that the force required to slide a 5000 N weight up a 10-m ramp to a height of 1 metre is much less than 5000 N. In fact, if the friction between the load and the ramp is very low, the force to slide the object would be reduced to almost 500 N $\left(\frac{\text{load}}{\text{Force}} = 10\right)$. The mechanical advantage in this case would be ten. By increasing the distance over which the force acts, by making the ramp longer for the same height, we can further reduce the force to do the task. The force required to slide the 5000 N weight up frictionless ramps of various lengths to a height of 1 metre is shown in the sketches below (Fig. 12.7).



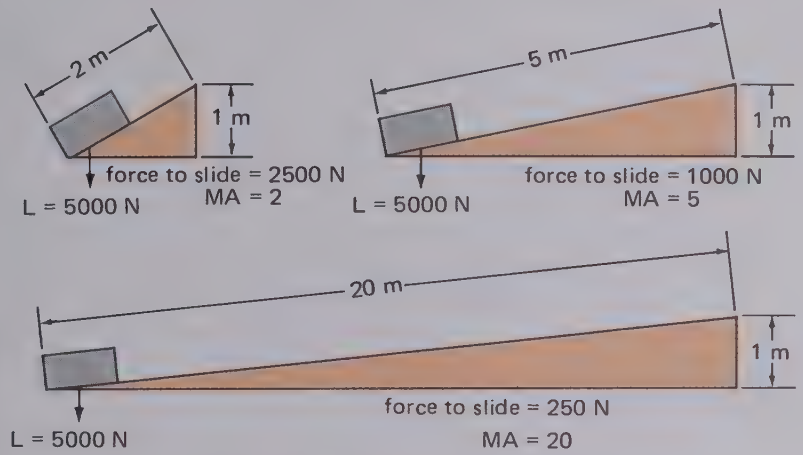


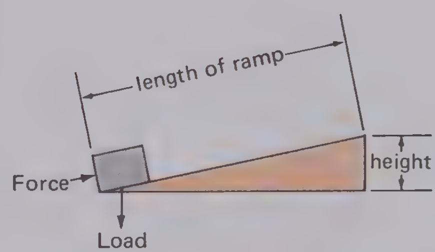
Fig. 12.7

The equation which describes this ideal, frictionless ramp is:
Force × Length of ramp = Load × Height

Man's preference for exerting a decreased force over a much longer distance to exerting a large force over a small distance is evident in the fact that he uses an inclined plane in many cases in which the friction between the load and plane is very high. Consider the following example:

An object of weight 3000 N is slid up a 10-m ramp to a height of 1 metre. The force required to slide the object on the ramp is 1000 N.

Let us compare the force and energy required to use the ramp as compared to doing the task directly.



Activity 12.1, *Inclined Plane*.

To lift directly

$$
\begin{aligned}
\text{Force required} &= 3000\ \text{N} \\
\text{Work done} &= F \times d \\
&= 3000\ \text{N} \times 1\ \text{m} \\
&= 3000\ \text{joules.}
\end{aligned}
$$

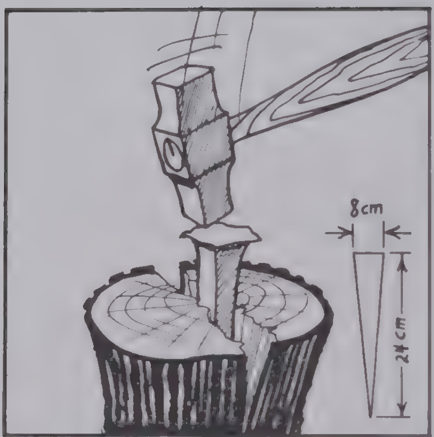
To use the ramp

$$
\begin{aligned}
\text{Force required} &= 1000\ \text{N} \\
\text{Work done} &= F \times d \\
&= 1000\ \text{N} \times 10\ \text{m} \\
&= 10{,}000\ \text{joules.}
\end{aligned}
$$

The actual mechanical advantage of the ramp is $\frac{3000\text{ N}}{1000\text{ N}} = 3$, but in using the ramp 10,000 joules of work are done compared to only 3000 joules if the object were lifted directly. The advantage of using the inclined plane in this example is certainly not to save energy but to exert less force. The 10,000 joules of energy used to move the object up the ramp is made up of two parts:

1) 3000 joules that go into the increased potential energy of the load,

2) 7000 joules that represent the energy "lost" in the form of heat and sound as a result of friction between the ramp and the load. If this force of friction is reduced, the energy lost will be reduced and we approach the ideal situation in which all energy goes into the potential energy increase of the load. In the ideal case, the mechanical advantage of the ramp is ten.

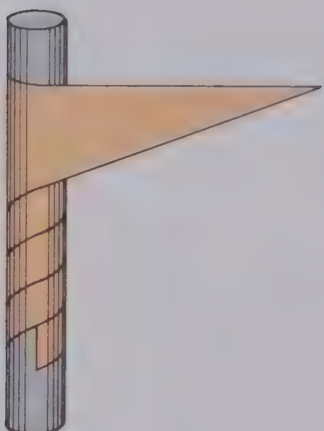


Q7 a) What force must be applied to slide a 200-kg object up a 8-m frictionless ramp to a height of 2 m?
b) How much work is done?
c) What is the mechanical advantage of the ramp?

Q8 The design of a wedge used in splitting logs is shown in the marginal sketch. If a force of 100 N is applied to the top of the wedge, what force is exerted on the log being split?

Q9 Since in every case that a ramp or wedge is used the forces of friction are such that much more work must be done than if the tasks were done directly, why do we use ramps and wedges?

e) The Screw



The last simple machine, the screw, is essentially a wedge wound around an axis. The distance between the threads of the screw is called the pitch and equals the distance the screw travels in one rotation. A force is applied to the screw by some form of lever which causes it to rotate. A very high mechanical advantage may be achieved using this design. Consider the jackscrew, described below (Fig. 12.8), which is used to lift corners of small buildings or heavy trucks.

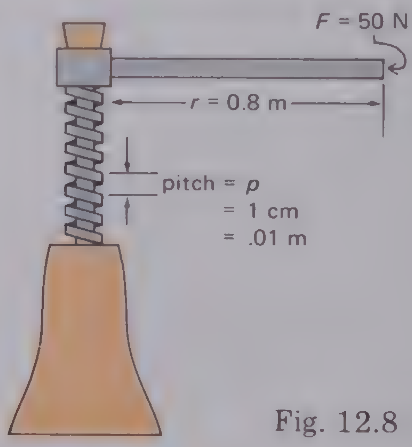


Fig. 12.8

If a force of 50 N is applied to the handle of the jackscrew through one rotation, the work done:

$$\begin{aligned} F \times d &= F \times 2\pi R \\ &= 50\text{ N} \times 2\pi(0.8\text{ m}) \\ &= 250\text{ joules (approx.).} \end{aligned}$$

This lifts the load the distance of the pitch = 0.01 m.

Therefore, we can calculate the load that can be lifted by this device assuming no energy loss.

$$\begin{aligned} \text{Work done} &= \text{load} \times \text{height lifted} \\ 250\text{ joules} &= \text{load} \times 0.01\text{ m} \\ \text{Load} &= \frac{250}{0.01} = 25{,}000\text{ N.} \end{aligned}$$

The ideal mechanical advantage of this jackscrew is

$$\frac{\text{force produced (load)}}{\text{force applied}} = \frac{25{,}000\text{ N}}{50\text{ N}} = 500.$$

Even if there were a 50 percent energy loss in this device, it would still produce a very large increase in the force.

Activity 12.2. *The C-Clamp as a*

Q10 In order to lift a 3000-kg object, a jackscrew of pitch 0.5 cm and a handle of length 0.8 m is used. What force must be applied to the end of the handle to lift the object? What is the ideal mechanical advantage of this jack?

*Q11 Why is the screw described as a wedge wound around an axle? How can this description be used to calculate the ideal mechanical advantage of the screw?

In ancient times the availability of the human muscle power of slaves made unnecessary the more efficient use of human energy. The ancient engineer was able to exert greater force simply by adding more bodies to the task. He did not need to invent machines to increase the efficiency of his efforts. The pyramids, a testament to the energy available in human muscles, were constructed before the Egyptians had the wheel. As we have seen, five simple ancient machines discussed in this section form the basis for the design of many mechanical devices of our modern society. With these simple tools, powered by human muscle, man is able to perform remarkable tasks.

With the development of more complex machines has also come the search for sources of energy to operate machines. These sources have changed during the past two thousand years from human muscle to nuclear energy. We shall consider the evolution of the energy sources which power man's machines in the next section.

Summary Chart For Simple Machines

Machine	*Equation*	*Ideal Mechanical Advantage*
The Lever	$F \times FA = L \times LA$	$MA = \frac{FA}{LA}$
Wheel and Axle	$F \times FA = L \times LA$ or $F \times$ Diameter of Force Wheel $= L \times$ Diameter of Load Axle	$MA = \frac{FA}{LA}$ $MA = \frac{\text{Wheel diameter}}{\text{Axle diameter}}$
Pulley	$F = \frac{L}{\text{Number of ropes supporting load}}$	$MA =$ Number of ropes supporting load
Inclined plane	$F \times$ length of ramp $= L \times$ height	$MA = \frac{\text{length of ramp}}{\text{height}}$
Jackscrew	$F \times 2\pi R = L \times$ pitch	$MA = \frac{2\pi R}{\text{pitch}}$

*Q12 A Problem in Machine Design
Design a complex machine (made up of simple machines) that could raise a 500-kg object to a height of 2 m without requiring an input force greater than 200 N. The machine should be of workable dimensions.

A model of Heron's aeolipile. Steam produced in the boiler escapes through the nozzles on the sphere, causing it to rotate. (An application of Newton's third law of motion.)

12.2 Sources of Energy

The shift of energy sources from human muscle to nuclear energy was a gradual technological development extending over two thousand years. It is the result of man's every increasing need for more energy to operate his machines and thereby increase his living standards. Social pressures eventually forced an elimination of the exploitation of human energy. Increased exploration resulted in the discovery of untapped energy reserves and in turn the invention of more complex machines increased the energy required. However there must always be a need before society will recognize an idea or invention as being useful. A simple form of the steam engine, invented by Heron, was used as a toy by the Greeks and not further developed. The water wheel was known by the Romans but not used. Because human and animal power was readily available in the early civilizations, it remained the source of energy for their simple machines. They did not make use of other sources of energy although in many cases the opportunity presented itself. The shift of energy sources from man and beast to the winds and rivers was a major step in the energy revolution.

The Domesday book, compiled in 1086, lists over 5000 mills in England powered by water wheels. Water wheels were later to operate the bellows of the blast furnaces of the early

metal industry. A contemporary adaptation of the water wheel is the turbine in a hydro generating station. The wind, used to push sailboats since antiquity, was harnessed for industry in the twelfth century. In the seventeenth century as a result of improvements in machine design, water and wind produced several kilowatts of useful power. However, such energy sources as wind and water were dependent upon terrain and climatic conditions and so other sources were sought.

The Marly works which pumped water to Versailles had a power output of 56 kilowatts.

The period from 1750 to 1850 is known in British history as the industrial revolution. It was a period in which man's use of energy was greatly increased as a result of demand and consequent invention. The industrial revolution marked a turning point from an agricultural to an industrial existence for much of the British population. Small farms were combined to form fewer and larger ones. The rate of population increase changed from one with a doubling time of 234 years in 1750 to one of 50 years in 1850. The many persons displaced from the farms became an inexpensive labour source for the early industries. The development of the steam engine was part of this age. The first commercially successful steam engine was developed in 1698 by Thomas Savery to pump water from mine shafts. This engine was improved by James Watt in 1765 so that it produced an output of about 10 kilowattts. Following its use as power for mining pumps the steam engine soon provided energy for railway engines to move coal from the mines. During the period from 1780 to 1880 coal production in England increased by a factor of 15 to provide heat for the blast furnaces of Europe. (During this same period the production of iron ore increased by more than 100.) Some schematic diagrams and operational details of these early engines are provided on separate pages in this section. Because of our modern view of large corporations operating research centres employing teams of scientists and engineers, it is interesting to note that these early engines were the work of a few self-taught individuals.

Thomas Savery (1610-1715)—English military engineer.

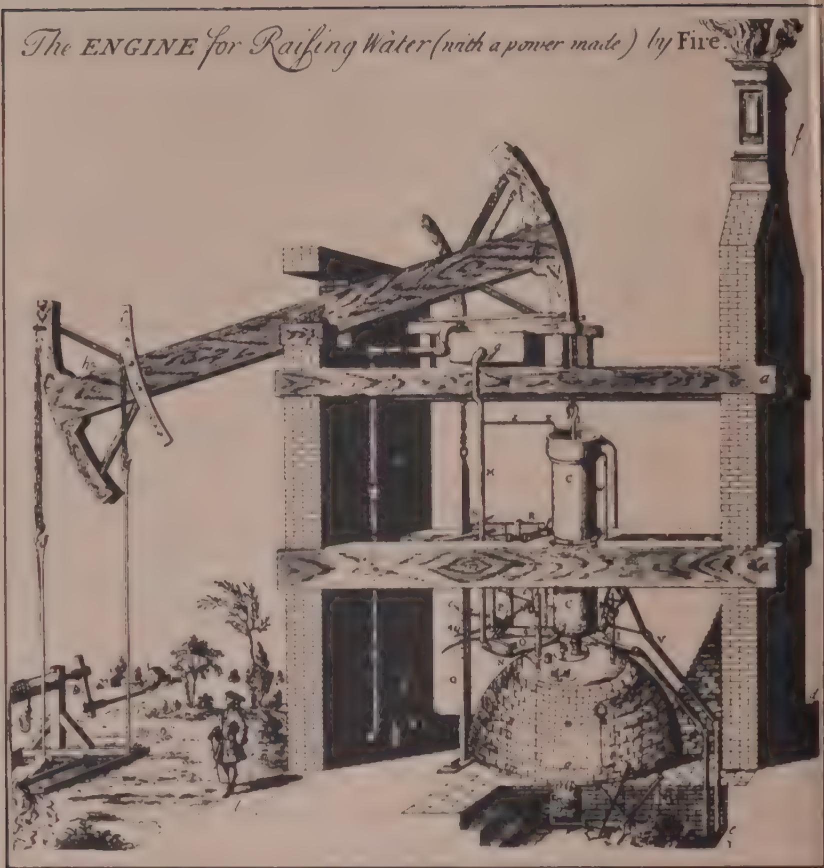
James Watt (1736-1819)—Scottish engineer.

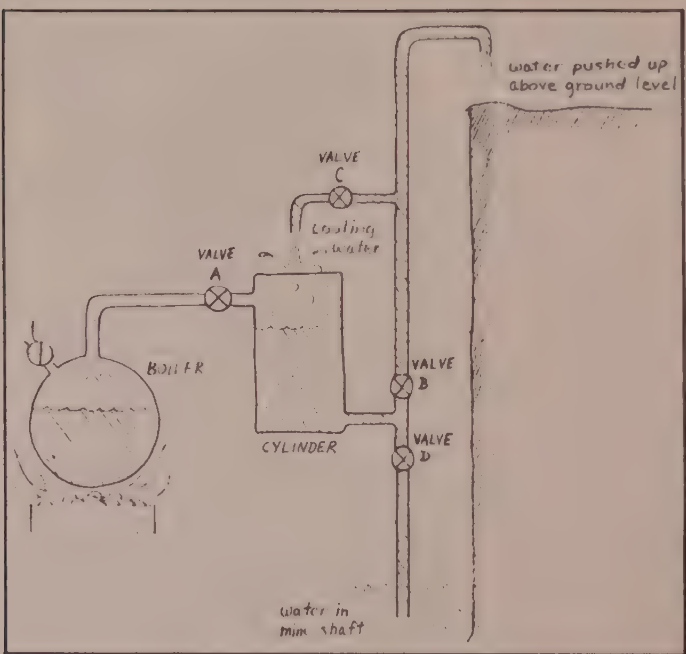
The use of coal as a major energy source marks another turning point in man's use of energy resources. Until he participated in the large-scale consumption of coal, man's energy sources had been renewable. Fields had continued to produce crops for food energy on a small scale without apparent loss in efficiency. Trees used in construction and as fuel were planted and harvested again within a human lifetime. But the earth's coal deposits, products of millions of years of decomposition, are a part of an irreplaceable and finite energy reserve. However, to the citizen of the industrial revolution, the transition of energy sources from the renewable to the nonrenewable caused less concern than his transition into his new urban surroundings. The town not only became an energy and employment centre, but it also became a centre of child labour, deteriorating family relationships, and ill health. Thus the triumph of technology was accompanied by a social disaster. Social reforms were soon to follow the technological revolution.

Suggested reading for a description of conditions during the Industrial Revolution:
Philip A. M. Taylor, *The Industrial Revolution in Britain* (Problems in European Civilisation) D. C. Heath and Company.

C. Stewart Doty, ed. *The Industrial Revolution* (European Problem Studies) Holt Rinehart Winston 1969.

At the right, a contemporary engraving of a working Newcomen steam engine. In July, 1698 Savery was granted a patent for "A new invention for raising of water and occasioning motion to all sorts of mill work by the impellent force of fire, which will be of great use and advantage for drayning mines, serving townes with water, and for the working of all sorts of mills where they have not the benefit of water nor constant windes." The patent was good for 35 years and prevented Newcomen from making much money from his superior engine during this period.





In the Savery engine the water in the mine shaft is connected by a pipe and valve *D*, to a chamber called the cylinder. With valve *D* closed and valve *B* open, high-pressure steam from the boiler is admitted to the cylinder through valve *A*, forcing the water out of the cylinder and up the pipe. The water empties at the top and runs off at ground level. Then valve *A* and valve *B* are closed and valve *D* is opened, allowing an open connection between the cylinder and the water in the mine shaft.

When valve *C* is opened, cold water pours over the cylinder, cooling the steam left in the cylinder and causing it to condense. Since water occupies a much smaller volume than the same mass of steam, a partial vacuum is formed in the cylinder, allowing the pressure of the air in the mine to force water from the mine shaft up the pipe and into the cylinder.

The same process, started by closing valve *D* and opening valves *A* and *B*, can be repeated over and over. The engine is in effect ■ pump, moving water from the mine shaft to the cylinder and in another step, pushing it from the cylinder to the ground above.

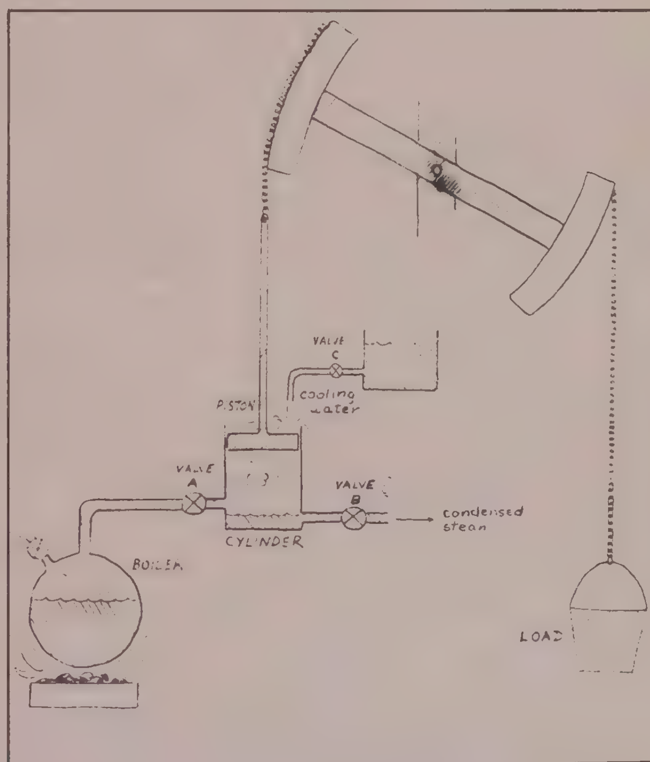
The Newcomen Engine (1698)

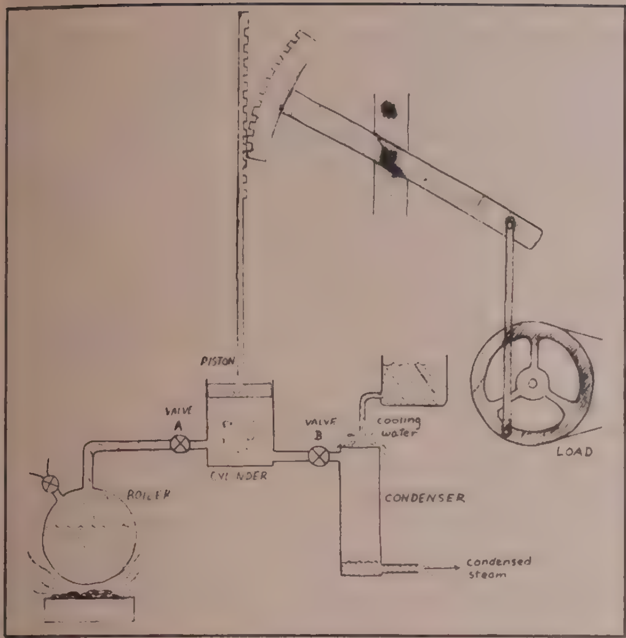
A serious disadvantage of the Savery engine was its use of high-pressure steam, which produced a risk of boiler or cylinder explosions. This defect was remedied by Thomas Newcomen (1663-1729) another Englishman, who invented an engine that used steam at low pressure. Also Newcomen's engine could raise loads other than water.

In the Newcomen engine there is a rocking beam connected to the load on one side and a piston in a cylinder on the other side. This beam is balanced in such a way that when valve *A* is open and the cylinder is filled with steam at normal atmospheric pressure, the weight of the load raises the piston to the upper end of the cylinder. While the piston is coming toward this position, valve *A* is still open and valve *B* is still closed.

But when the piston has reached its highest position, valve *A* is closed and valve *C* is opened. Cooling water flows over the cylinder and the steam condenses, making a partial vacuum in the cylinder, allowing the pressure of the atmosphere to push the piston down. As the piston reaches the bottom of the cylinder, valve *C* is closed and valve *B* is opened briefly to let out the cooled and condensed steam. Then valve *A* is opened and the cycle begins again.

Originally it was necessary for someone to open and close the valves by hand at the proper time in the cycle, but later a method was devised for doing this automatically. The automatic method used the rhythm and some of the energy of the moving parts of the engine itself to control the sequence of operation. This idea, of using part of the output of the process to regulate the process itself, is called "feedback"—and it is an essential part of the design of many modern mechanical and electronic systems.





The Watt Engine (1765)

In the winter of 1763-1764, Watt was asked to repair a model of Newcomen's engine that was used for demonstration lectures in classes at the university. In familiarizing himself with the model, he was impressed by how much steam was required to run the engine. Watt undertook a series of experiments on the behaviour of steam and came to realize that a major problem was the temperature of the cylinder walls. He observed that Newcomen's engine wasted most of its heat in warming up the walls of its cylinder, which were then cooled down again every time the cold water was injected to condense the steam.

Early in 1765, Watt saw how his wasteful defect could be remedied. He devised a modified type of steam engine in which the steam in the cylinder, after having done its work of pushing the piston up, was admitted to a separate container in order to be condensed. With this system, the cylinder could be kept hot all the time and the condenser could be kept cool all the time.

The diagram above represents Watt's engine. If valve *A* is open and valve *B* is closed, steam under pressure enters the cylinder and pushes the piston upward against the load. When the piston nears the top of the cylinder, valve *A* is closed to shut off the steam supply. Then valve *B* is opened, so that steam leaves the cylinder and enters the condenser. The condenser is kept cool by water flowing over it, so the steam condenses. As steam leaves the cylinder, the pressure there decreases and atmospheric pressure (helped by the inertia of the flywheel) pushes the piston down. When the piston reaches the bottom of the cylinder, valve *B* is closed and valve *A* is opened, admitting steam into the cylinder and starting the cycle of operations again.

Although Watt's invention of the separate condenser might seem to be only a small step in the development of steam engines, it turned out to be a decisive one. Not having to reheat the cylinder again and again allowed Watt's engine to do more than twice as much work as Newcomen's engine with the same amount of fuel. As a result of this saving in fuel cost, Watt was able to make a fortune by selling or renting his engines to mine owners.

Almost 100 years after Watt's steam engine the internal combustion engine was designed. This small, light and efficient engine was to become man's principle source of energy for personal transportation. We need not elaborate the effect that the automobile has had on our present life style. In North America the automobile has become a major factor in our economy. The automobile industry directly employs almost 10 percent of our labour force. It is only recently that the many consequences of automobile use have come under serious questioning. The internal combustion engine consumes oil and gasoline, which, like coal, are irreplaceable and finite energy sources.

At the same time as the invention of the internal combustion engine, the importance of electrical energy was recognized. Electricity provided the means to distribute energy efficiently over large distances. No longer was there the need to concentrate industry near the primary sources of energy. Electricity permitted the flow of large amounts of usable energy across countries. The development of electrical devices to do the work and increase the comfort of man precipitated a large increase in the consumption of fossil fuels to power the electrical generating stations. More recently a few electrical generating stations have been built to use nuclear energy to drive the steam through the turbines of their generators.

The first electrical power station for private consumers opened in New York City in 1882.

Until man understood the release of nuclear energy on earth, the origin of all our forms of energy could be traced to the sun. This has been discussed in the diagram on page 40, in the previous chapter. It is hoped that nuclear energy will provide a new source of energy which will reduce our dependence on the finite supply of fossil fuels. Experiments are also being carried out with other possible sources of energy. A generating station has been constructed at Passamaquoddy Bay which uses tidal flow to produce electrical energy for parts of the State of Maine. Steam from the earth's interior provides energy for electrical generators in New Zealand. Solar reflectors and cells not only provide electrical energy for satellites but directly heat houses and cook meals. But these sources at present, like nuclear energy, still form a small percentage of our total energy needs.

The book *Energy* in the Life Science Library discusses these and other possible energy sources.

*Q13 Make a chart showing man's changing sources of energy as a result of technological development during the past two thousand years.

*Q14 What was the significance of the industrial revolution in terms of energy sources and consumption?

Inventions 1700-1900

1680 Savery Engine

1698 Newcomb Engine

1700 ————————

1709 Iron smelting with Coke, (Abraham Darly)

1720 Sextant (John Hedley)

1733 Flying Shuttle, Weaving (John Kay)

1750 ————————

1761 Chronometer (John Harrison)

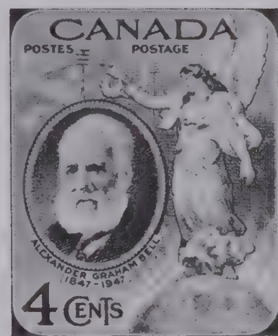
1765 Watt Engine (James Watt)

1768 Spinning Jenny (James Hargreaves)

1787 Power Loom (Edward Cartwright)

1793 Cotton Gin (Eli Whitney)

1800 Electric Battery (Alessandra Volta)



1800 ————————

1807 Steamship (Robert Fulton)

1814 Steam Railway Engine (George Stephenson)

1832 Sewing machine
Electric Generator
(Michael Faraday)

1844 Launching of first iron ship

1850 ————————
Bessemer Process (Pig Iron to Steel)

1876 Telephone (Alexander G. Bell)
Otto's Internal Combustion Engine

1879 Light Bulb (Thomas Edison)

1882 Electric Generating Station (Thomas Edison)

1885 Steam Turbine (Charles Parsons)
Motor Car (Carl Benz)
Pneumatic Tire (John Dunlop)

1896 Wireless (Marconi)
Diesel Engine (Rudolf Diesel)

1900 ————————

1903 Airplane flight (Orville and Wilbur Wright)

12.3 You Can't Get Something for Nothing, in Fact You Can't Even Break Even

Although the recent development of electrical and nuclear energy was the result of major discoveries in science, the early stages of the industrial revolution did not see scientific research leading to technological advancement. The development of the steam engine was a feat in practical engineering requiring only very basic scientific knowledge. The work done by the scientists of this time was largely theoretical and resulted in the recognition that heat was a measurable form of energy, that there was a law of conservation of energy, and that you cannot use heat energy with 100 percent efficiency. These statements have some interesting technological and philosophical implications.

The scientific developments of electrical and nuclear physics are discussed in Units 5 and 6 of the text.

The recognition that heat is a form of energy resulted in a statement of the law of conservation of energy which you have discussed in the preceding chapter. These ideas may be written as an equation in the following form:

$$\Delta E = \Delta W + \Delta H$$

where: ΔE represents the change in energy in a system,
ΔW represents the useful work done,
ΔH represents the heat energy produced.

This may be illustrated with the following example.

Consider a 10-kilogram object which falls to the ground from a height of 2 metres. (It could do work during this fall by attaching it to a rope over a pulley.) Its loss in potential energy is

$$\Delta E = 200 \text{ joules}$$

According to the equation,

$$\Delta E = \Delta W + \Delta H$$

the amount of work done by this object plus the heat produced when it falls equals 200 joules. Or to state it another way: If the "heat loss" (ΔH) equals zero, the maximum amount of work that could be produced is 200 joules.

PE = Force to lift × height
= 100 N × 2 m
= 200 joules.

The statement of the law of conservation of energy in this form is called the first law of thermodynamics and is sometimes informally stated "You can't get something for nothing."

Many scientists and inventors have tried to create perpetual motion machines. Some designs of such a machine would provide an energy output greater than the input. This would violate the first law of thermodynamics. Some designs for such machines are shown on page 67. The Canadian patent office has indicated its faith in the first law of thermodynamics by refusing to grant a patent for a perpetual motion machine based on a design only. A working model must be submitted.

Later it was recognized that the useful energy output of a machine can never be as much as the input and this modified the statement that you can't even break even. An analysis of machine efficiency was presented by a French engineer, Sardi Carnot, in a book entitled, *Reflections on the Motive Power of Fire* (published 1824). Carnot raised the question: Is there a

Leonardo da Vinci proposed a design in which large spherical bulbs were partially filled with mercury. He suggested that the shifting weight of the mercury would keep the wheel and by a gear arrangement, an axle turning.
He later wrote "O speculators about perpetual motion, how many vain chimeras have you created in your quest? Go and take your place with the seekers after gold."

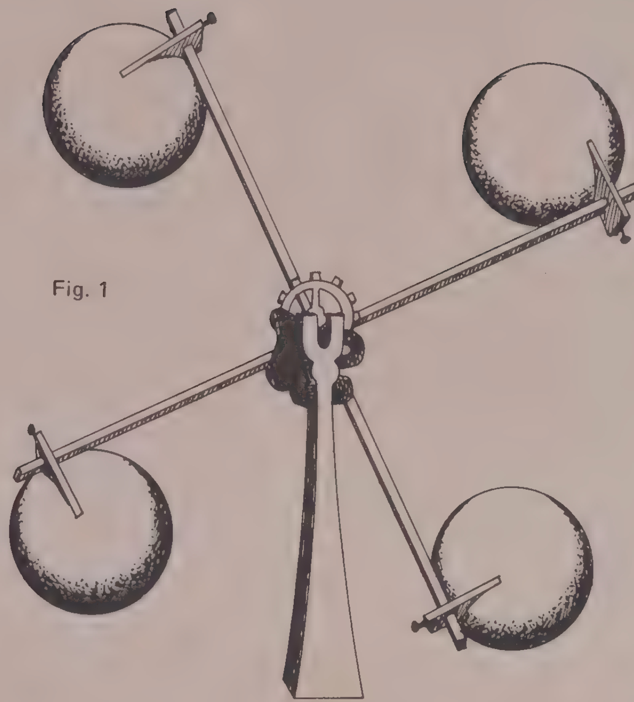


Fig. 1

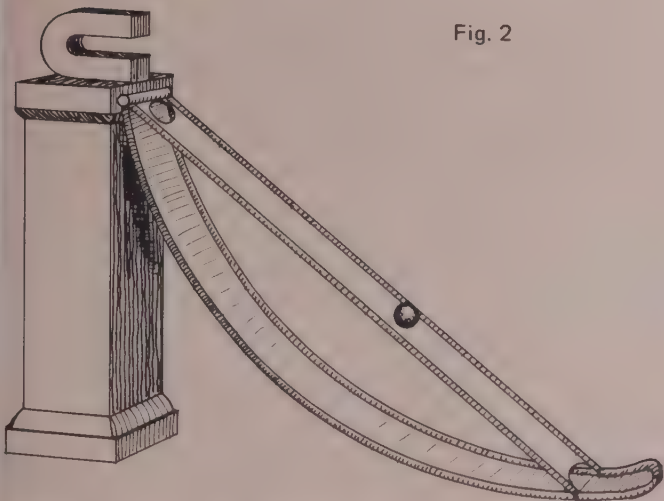
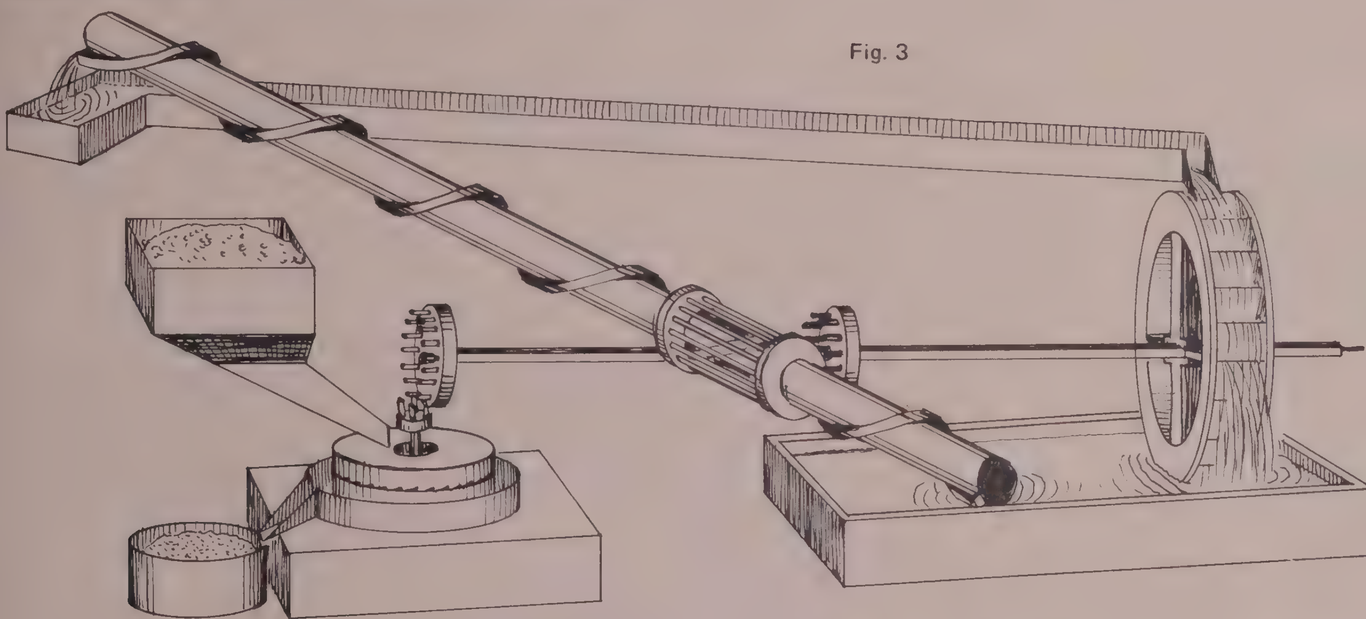


Fig. 2

A design similar to the device in Fig. 2 was proposed by the Bishop of Chester in the 1670's—The ball is drawn up the ramp by the magnet. It falls through the hole and returns to its starting point from which it is drawn up the ramp by the magnet. It then falls . . .

Fig. 3



The plan (Fig. 3) for the operation of a mill for regions without rivers was proposed by Robert Fludd in 1618.
An excellent article about perpetual motion machines was written by Stanley Angrist in the January 1968 issue of *Scientific American.*

maximum possible efficiency of an engine? The first law of thermodynamics of course, requires a limit of 100 percent—the energy output can never be greater than the energy input. But, by an analysis of the flow of heat in the engine, Carnot proved there is a maximum efficiency that is always less than 100 percent. There is a fixed upper limit on the amount of mechanical energy that can be obtained from a given amount of heat by using an engine, and this limit can never be exceeded regardless of what substance—steam, air or anything else—is used in the engine.

In addition to the existence of this limit on efficiency even for ideal engines, real engines operate at still lower efficiency in practice. For example, heat usually leaks from the hot parts of the engine to the cooler parts without passing through the part of the engine where this natural flow can be put to use to generate mechanical energy.

Modern steam engines have a theoretical limit of about 35 percent efficiency—but in practice they seldom have better than 20 percent.

Carnot's analysis of steam engines shows that there is an unavoidable waste of mechanical energy, even under ideal circumstances. The total amount of energy that was in the high-temperature steam, is conserved as it passes through the engine; but only part of it is transformed into useful mechanical energy. The rest is discharged in the exhaust and joins the relatively low temperature pool of the surrounding world. Carnot's reasoning led to the conclusion that there always must be some such release of heat from any kind of engine. It is this rejected heat that dissipates into the surroundings and becomes unavailable for useful work.

These conclusions about heat engines were incorporated into thermodynamics and became the basis for formulating the second law of thermodynamics. This law has been stated in various ways, all of which are roughly equivalent. The second law of thermodynamics may be stated as:

In a closed system, heat flows out of one part of the system and cannot be transformed wholly into mechanical energy (work), but must be accompanied by heat flow to a cooler part.

It expresses the idea that it is impossible to convert a given amount of heat fully into useful work.

*Q15 Examine the proposed perpetual motion machines on page 67. Can you see any plans in their design that would explain their inability to operate?

*Q16 Summarize the ideas expressed by the first and second laws of thermodynamics.

12.4 Canada's Energy: Supply and Demand

Canada in the 1970's has a population of over 22 million. It is a country relatively rich in natural resources used as primary energy sources in the forms of hydro power, natural gas, petroleum, coal and uranium. The energy policy of a nation depends upon: the ability of its scientists and engineers to detect

and develop methods of retrieving and refining its resources; the ability of its politicians and economists to decide policies concerning the production, import, and export of materials; and on the ability of industrialists and businessmen to determine the needs and to provide products for the market place. In Canada, additional problems concerning the transportation of energy and resources over large distances must be solved by a variety of specialists. It is sometimes more economical to import raw materials for one part of the country even though they are being exported from another part.

The chart on page 70 describing Canada's energy supply and demand for 1975 is based on projections published by the National Energy Board. We have made the following assumptions concerning the efficiencies of various utilities and machines:

Energy Supply and Demand in Canada and Export Demand for Canadian Energy NE23-669 Queen's Printer 1969.

The unit BTU has been used to permit reference to source material.

BTU = British Thermal Unit

1 BTU = 1.06×10^3 joules

Losses in production and transmission of electrical energy	= 69%
Efficiency of residential and commercial space heating	= 50%
Efficiency of transportation engines	= 30%
Efficiency of industrial use of energy	= 75%

This analysis shows the overall efficiency of our energy use to be about 45 percent. The "wasted energy" is mainly in the form of irrecoverable heat losses. You might like to compare this analysis with a similar study done for the United States published in the September 1971 issue of *Scientific American* magazine.

Reference: Earl Cook, "The Flow of Energy in an Industrial Society", *Scientific American*, September 1971, page 134.

Our future long range energy requirements have also been estimated by the National Energy Board and these are shown in the graph (Fig. 12.9). Population estimates are listed in the marginal chart for comparison.

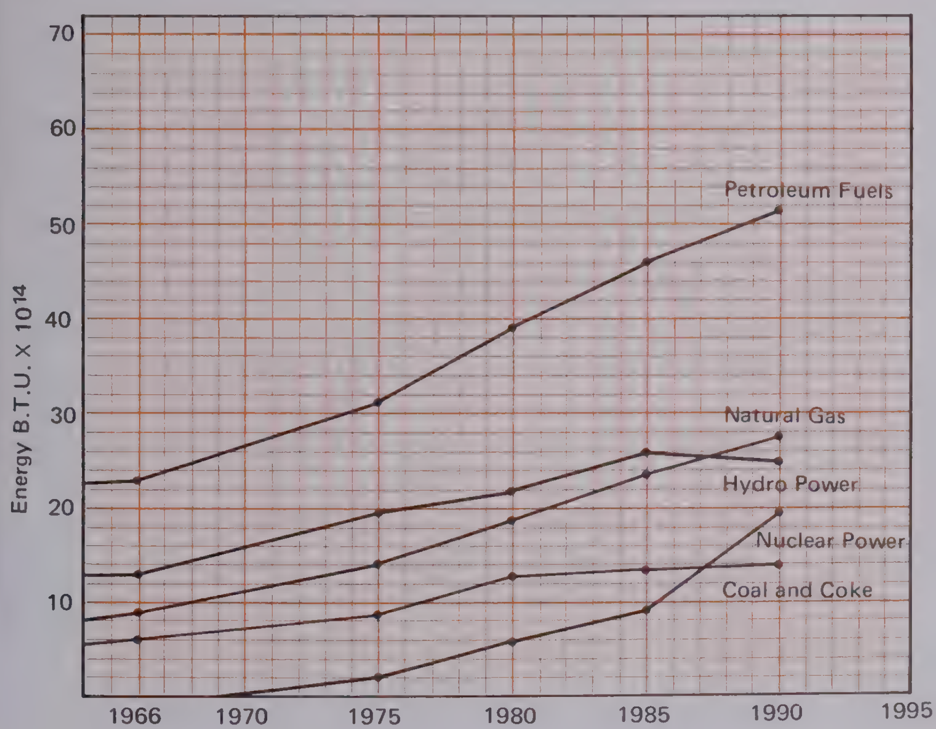
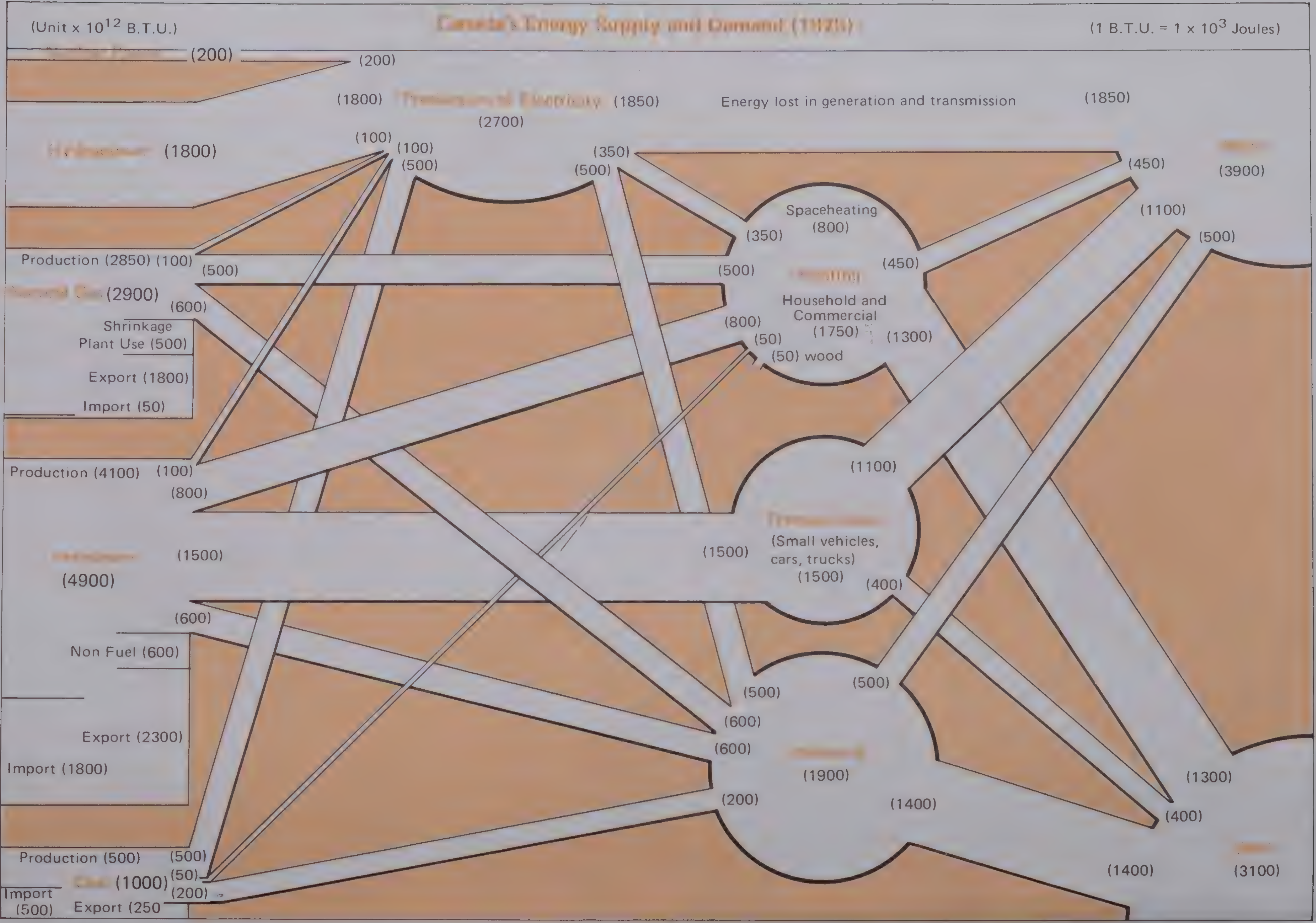


Fig. 12.9

Year	Population Estimate (X 1000)
1966	20,015
1975	23,349
1980	25,464
1985	27,793
1990	30,361


Canada's Energy Supply and Demand
(Unit x 10^12 B.T.U.)
(1 B.T.U. = 1 x 10^3 Joules)
(200)
(200)
(1800)
Thermal Electricity
(1850)
(2700)
Energy lost in generation and transmission
(1850)
Hydropower
(1800)
(100)
(100)
(500)
(350)
(500)
(450)
(3900)
Spaceheating
(800)
(350)
(450)
(1100)
(500)
Production (2850) (100)
(500)
(500)
Natural Gas (2900)
(600)
Household and
Commercial
(1750)
(1300)
Shrinkage
Plant Use (500)
(800)
(50)
(50) wood
Export (1800)
Import (50)
Production (4100)
(100)
(800)
(1100)
(Small vehicles,
cars, trucks)
(1500)
(1500)
(1500)
(4900)
(400)
(600)
Non Fuel (600)
(500)
(500)
(600)
(600)
Export (2300)
Import (1800)
(1900)
(200)
(1400)
(1300)
(400)
Production (500)
(500)
(1000)
(50)
(200)
Import
(500)
Export (250
(1400)
(3100)

The demands we will place on all primary energy sources will greatly increase from 1966 to 1990 as shown in Fig. 12.9. It is predicted that our demands for hydro power and petroleum will more than double, and our demands for natural gas and coal will increase to about three times the 1966 values. Also, there will be a much greater emphasis placed on the contribution of nuclear energy. Our increased use of energy resources will be briefly discussed in the next section.

We have presented a look at a nation's energy flow. Our presently used energy sources in Canada consist mainly of the hydro power that once powered the mills of the pioneers and now powers the turbines in electrical generating stations, and of fossil fuels that provided energy to the early inventions of the industrial revolution and now power our modern adaptations of their machines. This use is similar to that of other industrial nations. (Although the contribution made by hydro power in Canada is greater than in most other nations.) It is hoped that the many other questions raised by a look at Canada's energy network will be discussed in your other courses. Of particular interest are questions concerning the control of companies involved in primary energy resources, and in the export and import of natural resources. As the demands for energy by other countries increase, more pressure will be placed on Canada as a supplier of fuel.

*Q17 Using the Energy Supply and Demand chart for 1975, trace the use of one primary energy source completely across the page. Calculate the efficiency with which this primary source is changed into work.

12.5 The Energy Crisis

North Americans comprise only 6 percent of the world's population but they consume 40 percent of the world's resources and create over 50 percent of the world's waste.

The total solid waste generated in Canada this year would be sufficient to build a four lane highway from Toronto to Vancouver.

A 100-watt bulb lighted for ten hours uses the amount of energy that would be produced by the burning of 7 kilograms of coal in a thermal electric generator.

The statements above reveal an increasing concern felt by many individuals about the amount of energy we are using, the predicted increases in this amount, and the many pollutants which are end-products of our energy consumption. The realization that our energy resources present finite and largely irreplaceable commodities has resulted in the statement that we are heading towards an energy crisis.

The growing demand for energy in Canada can be illustrated by two graphs. The first (Fig. 12.10) shows the population from 1870 with predictions to 1990. The shape of this curve, which is similar to the shape of the graphs for most other countries, shows not only a rising population, but one in which the rate of the rise is also increasing. (This is indicated on the graph by the increase in the slope of the curve.) If we consider this graph alone, we could deduce that Canada's energy needs would have to increase

by a factor of 2.2 during the period from 1950 (population 13,700,000) to 1990 (population 30,400,000) just to keep pace with the population increase.

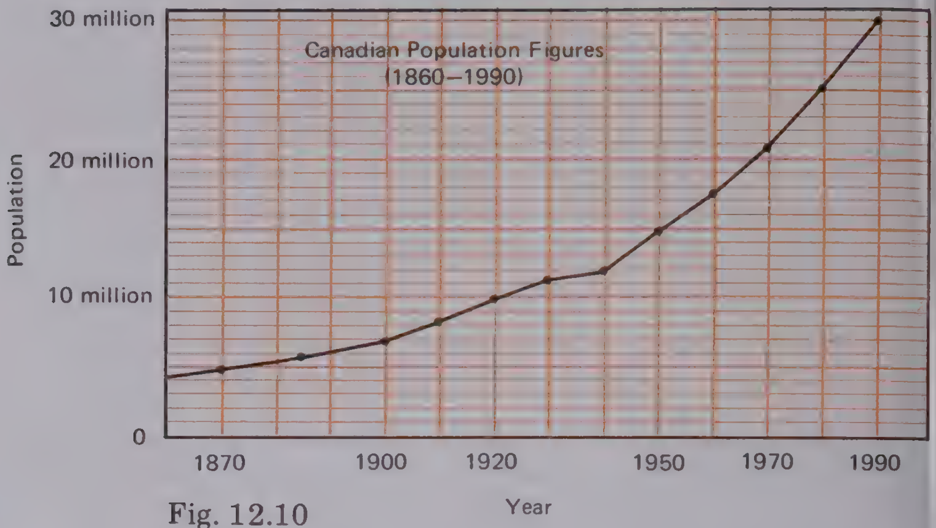


Fig. 12.10

The increasing needs of a growing population are a most important factor in a discussion of the energy crisis. Some books which discuss this population explosion are listed in the margin for your consideration.

Suggested Reading:

Ehrlich, Paul R.
The Population Bomb
New York: Ballantyne Books Inc. 1968

Ehrlich, Paul and Anne Ehrlich
Population, Resources, Environment
San Francisco: W. H. Freeman Publica tions, 1970.

However, each person's energy demands do not remain constant. We try to increase our standard of living, which means we use more energy. The graph (Fig. 12.11) shows the changing average electrical energy demand per person in Canada for the period from 1950 to 1990.

If the predictions displayed in this graph are correct, during the period 1950 to 1990, an individual's demand for electrical energy will increase by a factor of 5. This coupled with a predicted doubling of the population (actually 2.2) during the same period would produce an increase in energy demand of $2.2 \times 5 = 11$ times during a 40-year period.

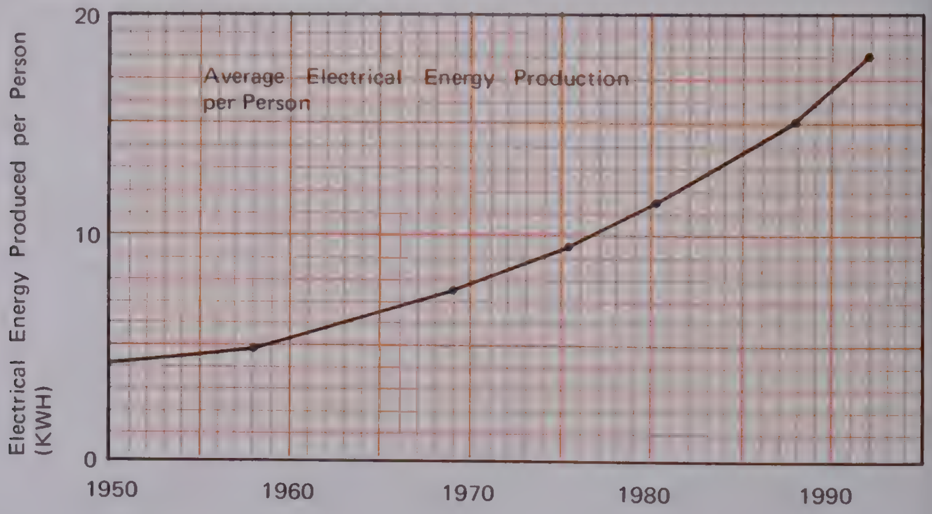
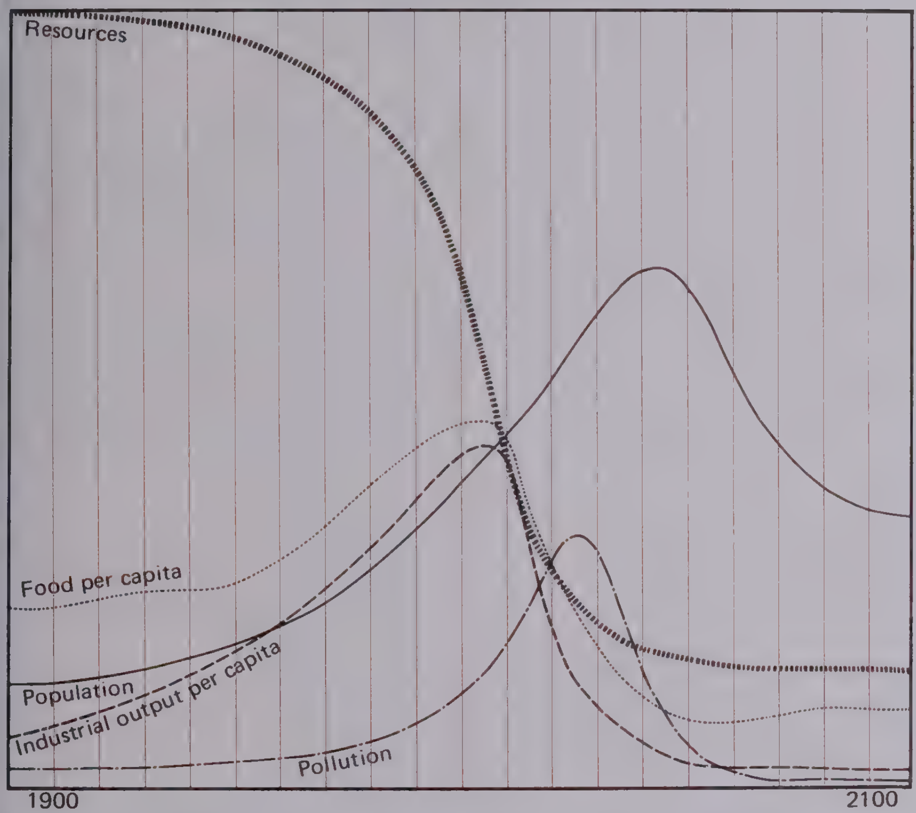


Fig. 12.11

The realization of the effect that such an increase will have on finite energy resources has caused many scientists and engineers to reconsider their roles in society. No longer do they see themselves as merely having to develop the technology and resources to satisfy society's energy demands. They are questioning these demands to make people aware of the implications of continuing population growth and rising energy demands. Some organizations have proposed a limit to an individual's annual energy consumption.

Not only are society's energy demands being reconsidered, but also the products created by industry's energy use. The no-return bottle made the slogan "no deposit—no return" a testament to the short-sightedness of affluence. How much longer can we replace instead of repair, bury instead of recycle, and pollute rather than enrich our environment? An analysis of the question—When will the energy crisis become acute?—has been carried out by the Club of Rome using computer simulations. Their results were published in *The Limits To Growth*, a Universe Book published in 1972. The graph and comments are based on one of their forecasts.

Graph and comments from *The Limits To Growth,* Meadows et al., Universe Books, 1972, page 124.



The "standard" world model run assumes no major change in the physical, economic, or social relationships that have historically governed the development of the world system. All variables plotted here follow historical values from 1900 to 1970. Food, industrial output, and population grow exponentially until the rapidly diminishing resource base forces a slowdown in industrial growth. Because of natural delays in the system, both population and pollution continue to increase for some time after the peak of industrialization. Population growth is finally halted by a rise in the death rate due to decreased food and medical services.

Unfortunately, the simulations based upon improved conditions do not appear to be much better.

Activity 12.5, *Energy and the Environment.*

The physics student can play a rather important role by explaining and questioning our use of energy. An understanding of the law of conservation of energy must lead to the question, Where does the energy come from?, when we hear talk of bringing all nations up to our standard of living, or plans of doubling and redoubling energy demands. We must become aware of our behaviour in terms of energy use. It appears that the remedy to the energy crisis may not be found in some new energy source, but rather, in a change in man's behaviour. He may have to restrict the high energy demands required to satisfy his material desires in favour of less energy-requiring services and education. Also, he must develop the science and technology to recycle all possible resources. We must remove the pollution products from industrial, commercial, and personal energy use. Products should be designed to last longer and be easily repaired. The concept that our earth is merely a large ship travelling through space with limited provisions must be understood.

*Q18 React to the following statements:

a) There is no shortage of food on the earth. It is simply a question of proper distribution.

b) Humanity's mastery of vast, inanimate, inexhaustible energy sources; the accelerated use of the decreasing resources of sea, and air; and space technology have proved Malthus to be wrong. Comprehensive physical and economic success for humanity may now be accomplished in one-fourth of a century.

c) The average North American eats daily, food that has consumed 13,000 litres of water in its production. If everyone ate like that there would not be a drop of water left on the land.

d) I don't pollute the air. My home is heated electrically.

The Primary Energy Consumed by One Year's Operation of a Dishwasher

A look at the effect of an appliance on our primary energy sources

The following assumptions have been made in this calculation:

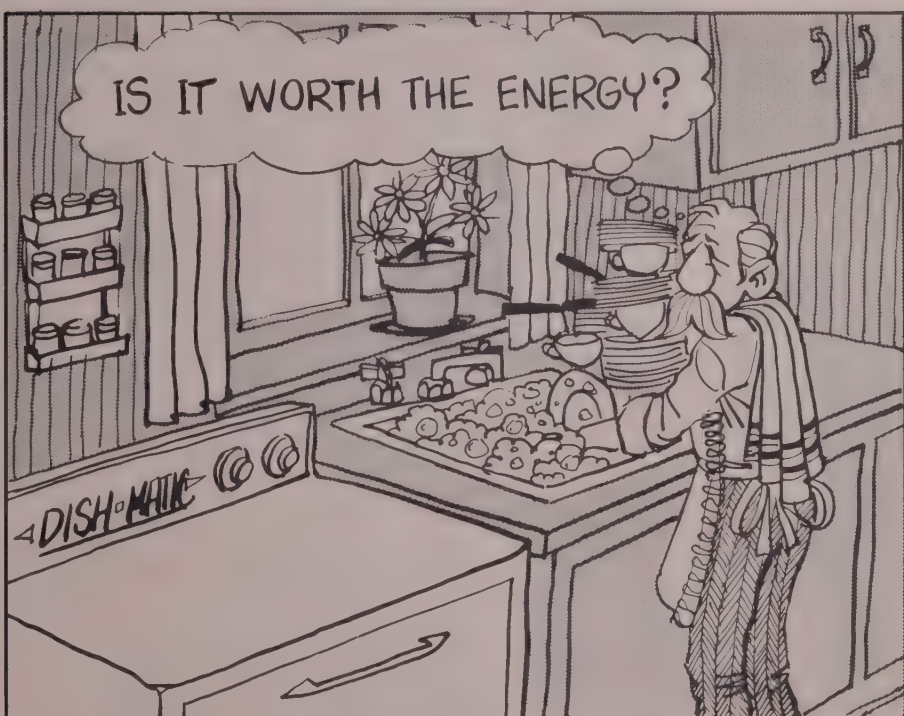
1. Dishwasher is used twice daily.
2. Each wash requires 24 litres of water, heated from 10°C to 85°C. (8 litres for each of 2 wash cycles and 1 rinse)
3. The drying cycle draws a current of 13 amperes (110 V) for 20 minutes. (Other electrical energy used in operation has been ignored in this calculation.)

Electrical energy per wash
To heat water $= 6.5 \times 10^6$ joules
To dry dishes $= 1.7 \times 10^6$ joules
Total $= 8.2 \times 10^6$ joules
Electrical energy per year $= 8.2 \times 10^6 \times 2 \times 365$
$= 6.0 \times 10^9$ joules.

To produce this electrical energy output a thermal generating station, assuming 33 percent efficiency, would require an input of

$$6.0 \times 10^9 \times \frac{100}{33} = 18.00 \times 10^9 \text{ joules}$$

This is approximately equivalent to the energy in
100 kg of sub-bituminous coal
500 cubic metres of natural gas
3 barrels (about 350 litres) of light fuel oil



Chapter 13 *Waves*

Waves

Chapter Thirteen

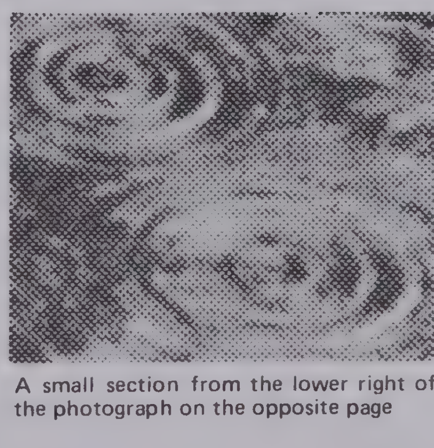
13.1 Waves: A method of energy propagation

Waves are all around us. Water waves, especially giant rollers in the middle of the ocean or gently formed rain ripples on a still pond, are sources of wonder or pleasure. If the earth's crust shifts, violent waves cause tremors thousands of miles away. A musician plucks a guitar string and sound waves pulse against our ears. Someone stumbles on a crowded dance floor and a wave of bumping or crowding spreads through the adjacent dancers. Wave disturbances may come in a concentrated bundle like the shock front from a single clap of the hands (or from an airplane flying at supersonic speeds), or the disturbances may come in succession like the train of waves sent out from a steadily vibrating source, such as an alarm clock.

As physics has progressed over the last hundred years, vibrations and waves of a less obvious kind have been discovered. Electromagnetic waves in particular have been found to be fundamental to nearly everything we can sense about our universe. Most of our explanations of energy transfer involve waves.

So far, we have been thinking of motion in terms of individual particles. As we begin to study the cooperative motion of collections of particles, we shall recognize how intimately related are the particle and wave models we make of events in nature.

If you look at a black and white photograph in a newspaper or magazine with a magnifying glass, you discover that the picture is made up of many little black dots printed on a white page (up to 3,000 dots per square cm). If you do not use the magnifier, you will not see the individual dots, but a pattern with all possible shadings between completely black and completely white. The two views emphasize different aspects of the same thing.



A small section from the lower right of the photograph on the opposite page

In much the same way, the physicist often has available several ways of viewing events. For the most part, a particle view has been emphasized in the first three units. In Unit 2, for example, we treated each planet as a particle experiencing the sun's gravitational attraction. The behaviour of the solar system was described in terms of the positions, velocities, and accelerations of pointlike objects, but this viewpoint is far from a complete description of our planetary neighbours. In Unit 3, momentum, work, and energy are defined, equations are stated, and calculations done involving these concepts. In Chapter 12, however, a different perspective on these topics is presented, as we look at man's invention of ways to use energy efficiently and the effects this had had on our environment.

Now we are about to study waves, and once again we find an alternative point of view. Most of the waves discussed in this chapter can be described in terms of the behaviour of particles, but we also want to understand waves as disturbances travelling in a continuous medium. We want, in other words, to see the picture as a whole, not only individual dots.

13.2 Transverse Pulses and Waves

A **wave** *can be defined as a phenomenon by which energy propagates through distances as a result of vibratory motions.*

A mechanical wave is one in which actual bodies or particles undergo the vibrations. There are wave disturbances in which no material bodies actually move, the wave energy propagating instead by electric and magnetic fields. In Unit 5, you will learn that such waves are responsible for what we call light. However, in all waves, the effects produced depend upon the flow of energy as the wave moves forward.

Experiment 13.1, *How Pulses Travel.*

A rope provides a good medium to discuss mechanical waves. If energy is given to the left end of the rope in Fig. 13.1 by quickly raising it a distance above its rest position and then lowering it back again, a wave pulse will travel the length of the rope. If we watch the markers along the rope, we shall see them rise and fall at the same rate as the left end of the rope was moved. Although the motion of the markers indicates that energy has been transmitted horizontally along the rope, the only motion of the medium was perpendicular to this direction. This is a characteristic of a *transverse pulse.*

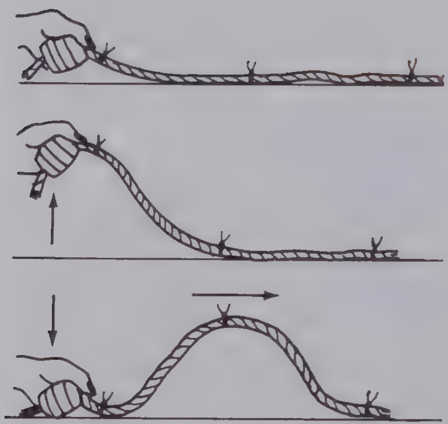


Fig. 13.1 A transverse wave pulse

If we call any positions of the medium above the equilibrium position positive, then this pulse would be called a positive wave pulse, because all displacements of the medium produced by it are in the direction we have called positive. A negative wave pulse could be produced by moving the spring below its rest position and then raising it back to its starting position.

The magnitude of the maximum displacement of the medium from the equilibrium position is called the **amplitude** of

the pulse. The amplitude of the pulse sketched in the margin is 2 cm.

Activity 13.6, *Wave Machine.*

If the rope is raised above and lowered below its rest position in one smooth motion, a complete wave comprised of a positive and negative pulse travels along the rope. Particles having maximum displacements are said to be either at a crest, if they are above the equilibrium position, or at a trough, if they are below the equilibrium position. *The particles of the medium vibrate perpendicular to the direction of energy transfer.* This is called a **transverse wave.**

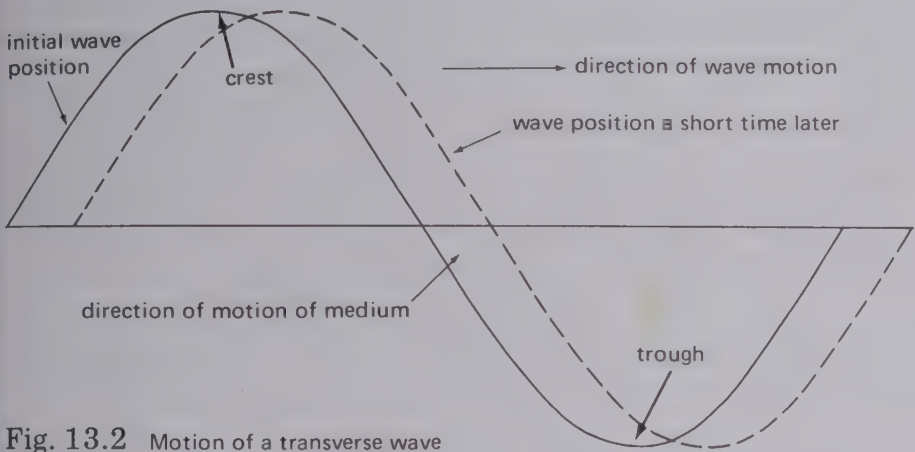


Fig. 13.2 Motion of a transverse wave

In Fig. 13.2, the position of a transverse wave is indicated with a solid line. The dotted line shows the position of the wave a short time-interval later. During the interval, each section of the medium has risen or fallen in the manner marked in the diagram. The height each point along the rope reaches before it falls toward the equilibrium position depends on the amount of energy provided at the source. But the gain in the potential energy of each part of the rope can be no greater than the energy input at the source.

If no heat energy were produced in the coil or the surrounding medium, the wave pulse should continue down the medium with the same amplitude. In real systems, the wave amplitude decreases, indicating the transformation of mechanical energy into heat. The reduction in amplitude of a wave due to the dissipation of wave energy as it travels away from the source (as shown in Fig. 13.3) is called *damping.* Damping effects may be quite small over short distances, and we will usually ignore the effect in this course.

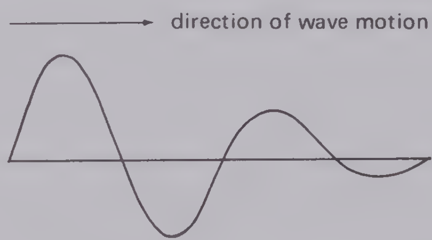


Fig. 13.3
A wave showing severe damping effects.

Q1 What is a wave?
Q2 Define a transverse wave.
Q3 Sketch a negative wave pulse of amplitude 2.5 cm. If it is imagined to be travelling from right to left on your page, mark on your diagram the direction of motion of particles in several sections of the wave pulse.
Q4 What becomes of the energy associated with a wave after the wave has been damped out?

13.3 Longitudinal Pulses and Waves

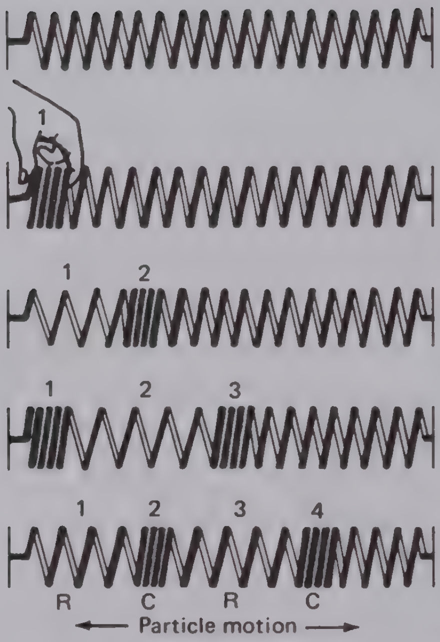


Fig. 13.4 A longitudinal wave

Now let us consider pulses and waves in a large coiled spring, but with the energy input applied in a different manner. This time work is done on the left end of the spring by squeezing a few coils together. This region, containing a higher concentration of the material of the medium than there was initially, is called a *compression.* If the spring is released, the coils will move to the right past their initial position, causing a compression in the medium at region 2 (Fig. C). But this leaves region 1 with a lower concentration of coils than it had initially. Such a region is called a *rarefaction.* The coils near the right of compression region 2 are pushed to their right, causing a compression in region 3. Coils to the left of compression region 2 (i.e., those that had moved forward from region 1) now move back toward region 1. Region 2 now becomes a rarefaction (Fig. D). The compression in region 3, by an identical process, moves to region 4. Region 3 by then has become a rarefaction. In this way the compression and rarefaction follow each other along the medium. The initial energy input which caused the coil disturbance at 1, has been transmitted along the spring by the vibratory motion of the coils. The "particles" of this medium, the coils, vibrate parallel to the direction of motion of the energy.

If the coils at one end of the spring are regularly squeezed and released, a continuous series of compressions and rarefactions travels along the spring. This is an example of a wave in which *the particles of the medium vibrate parallel to the direction of energy propagation.* It is called a **longitudinal wave**.

Q5 Define: a) a longitudinal wave
b) a compression
c) a rarefaction

13.4 Periodic Vibrations

Any body which moves back and forth over a definite path in equal intervals of time is said to undergo periodic motion. A swinging pendulum is a good example. Each swing is virtually a repeat of every other swing. Another example is the up and down motion of a mass attached to the end of a spring. *The magnitude of the maximum displacement from the equilibrium position is called the* **amplitude,** A, of the periodic motion. *The time taken for one oscillation* is called the **period,** T. *The number of vibrations per second* is the **frequency,** f. In the MKS system, the unit of frequency is the hertz. A frequency of two hertz tells us that the number of vibrations of the source was two per second.

$$f = 2 \text{ Hz} = 2 \text{ cycles per second.}$$

Notice the simple relationship between the period and frequency. If 2 vibrations are completed in one second ($f = 2$ Hz) then one vibration must have taken 1/2 second. ($T = \frac{1}{2}$ s). If $f = 10$ Hz, then $T = \frac{1}{10}$ s.

$$\text{In general, } T = \frac{1}{f}$$

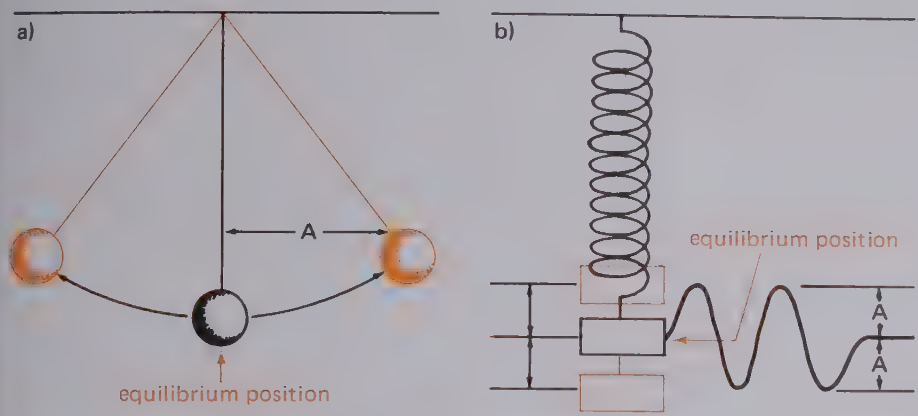


Fig. 13.5 Examples of Periodic Vibrations

Q6 Define: a) frequency
b) period

Q7 Define one hertz.

Q8 If a pendulum makes 20 vibrations in 10 seconds calculate
a) frequency
b) period

13.5 Periodic Waves in a Rope

Suppose we arrange for a continuous input of energy into a long rope by attaching a rope to a mass on a spring as in Fig. 13.5 b). If the spring is set into vibration, then a periodic transverse wave is produced in the rope. The particles of the medium vibrate continuously in a direction perpendicular to the direction of the wave motion. To describe the properties of such a wave, we shall introduce some wave terminology.

The phase of a wave refers to the displacements and instantaneous velocities of the particles of the medium. Examine the displacements of all the lettered particles in Fig. 13.6.

Notice that the displacements of particles at *B*, *D*, *J*, and *L*, *are* the same. Now examine the velocity vectors of these four particles. Notice that those of particles *B* and *J* are identical, as are the velocities of particles at *D* and *L*. Two particles such as those at *B* and *J* or *D* and *L* which have the same velocities *and* displacements at any one time are said to be *in phase*. *A* and *I*, *C* and *K*, *E* and *M* are other sets of particles vibrating in phase with each other. Two particles with displacements and velocities in the opposite directions are in opposite phase. *B* and *F* are in opposite phase.

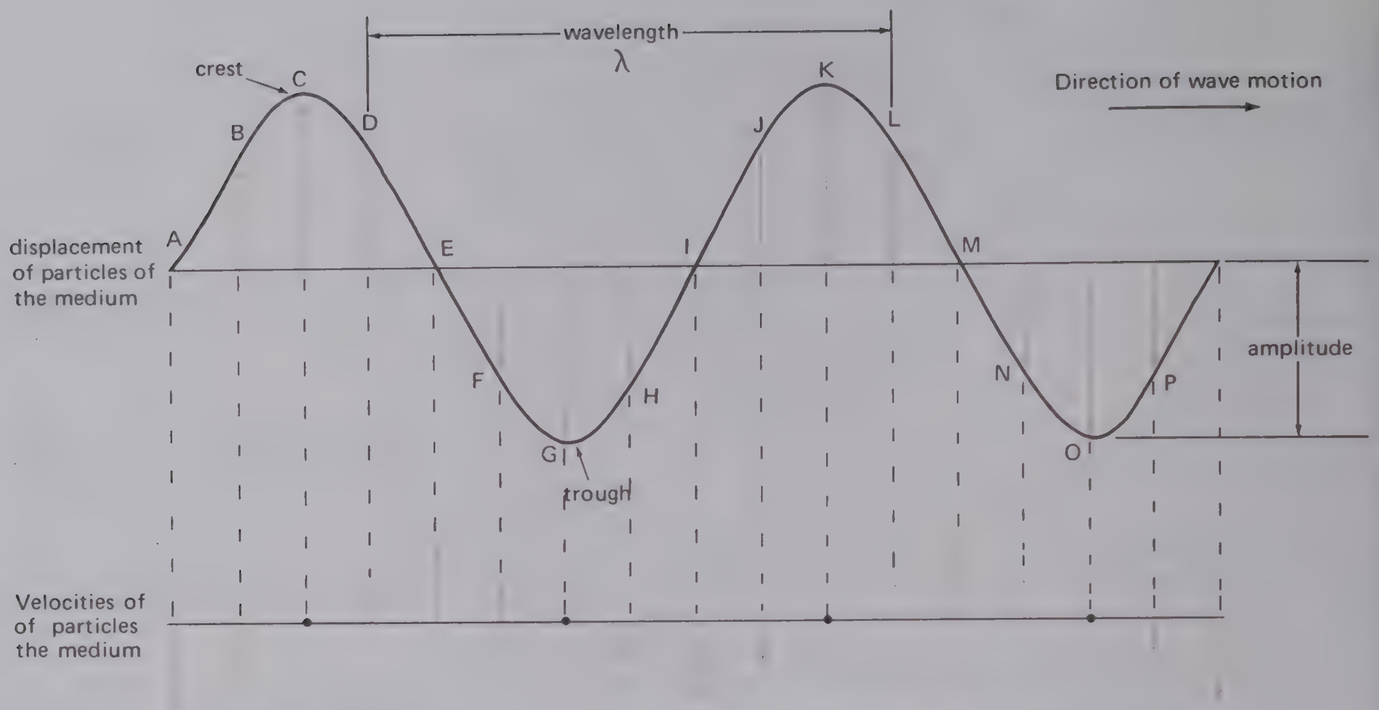
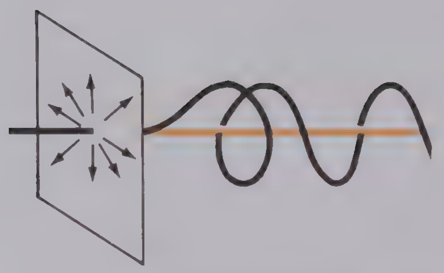


Fig. 13.6 Analysis of displacements and velocities of particles at one instant in a transverse wave. Can you pick out points that vibrate in phase with each other?

The distance between any two successive particles in the same phase is called **one wavelength** and is represented by the Greek letter lambda (λ). The distance between in phase particles, such as *D* and *L* is one wavelength of this wave.

The time required for the wave to travel one wavelength is called the **period** *(T)* of the wave. The period of the wave is always the same as the period of the source.

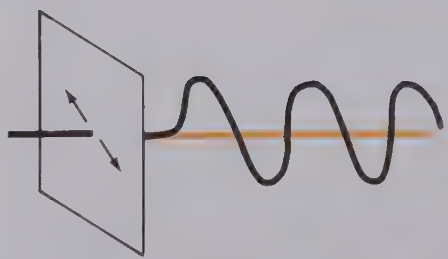
The frequency (f) of the source expresses the number of complete vibrations of the source per unit of time. In terms of the wave that is produced by these vibrations of the source, the frequency is the number of times any given phase of the wave passes by any one point in a unit of time. A wave with a source vibrating at 2 Hz would send two wave crests, or 2 troughs past any given point in the medium each second.



A. unpolarized wave on a rope

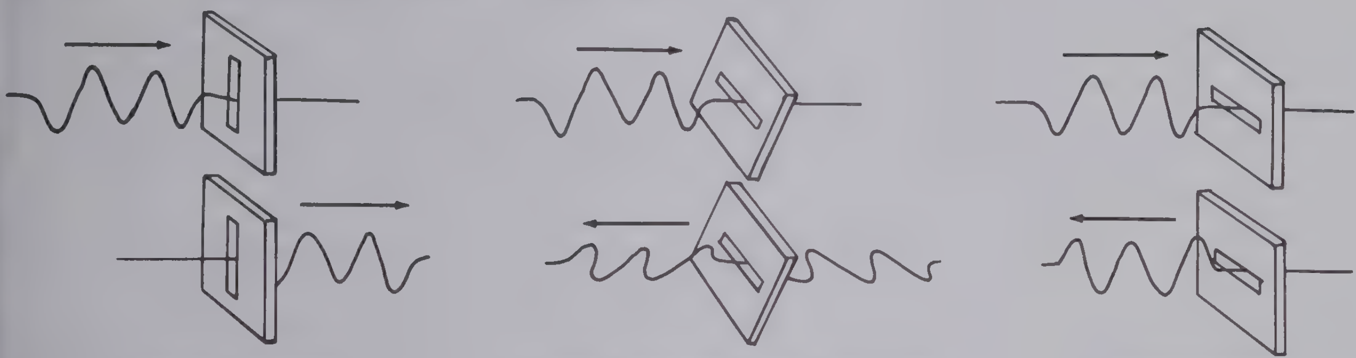
Polarization

In any transverse wave, the particles of the medium vibrate in a direction that is at 90 degrees to the direction of propagation of the wave. There are many possible planes of vibration, all fulfilling the above condition. The displacements of a transverse wave can be in any or all of an infinite number of directions, all of them at right angles to the direction of propagation of the wave. This is easily seen on a rope by shaking one end around randomly instead of straight up and down or straight left and right. For simplicity, the diagrams of waves in this chapter have shown transverse displacements in only one of all the possible planes. *Transverse waves in which the particles of the medium oscillate in one plane only are said to be* **plane polarized.**



B. polarized wave on a rope

Waves on coils or ropes can be seen and therefore we can observe a polarized wave directly. However, whether we can see the wave directly or not, there is a general test for finding out whether a wave is polarized: find some effect of the wave which depends on the plane of vibration. An example of the principle is illustrated in Fig. 13.7, in which the transmission of a rope wave is shown to depend on the angle at which a slotted board is held. Each of the three sketches begins with the same wave approaching the obstacle (top line). Whether the wave passes through (bottom line), depends on the angle the slot makes with the plane of the mechanical motion of the rope.



a) Complete transmission   b) Partial reflection and partial refraction   c) Complete reflection

Fig. 13.7

In general, if we can find some effect of a wave which depends similarly on the angular orientation of the obstacle or medium through which the wave must pass, we can conclude that the wave is polarized. Further, we can conclude that the wave must be transverse rather than longitudinal, since only transverse waves can be polarized. Some interesting and important applications of this principle will be discussed in Chapter 15.

Q9 Make a sketch showing 2 wavelengths of a transverse wave of wavelength 5.0 cm and amplitude 1.5 cm. Mark two points that are in phase, two points that are in opposite phase, and the wave crest and trough.

Q10 For the wave you drew for Q9, if the period of the source were 2 seconds, what would be the period of the wave? What would the wave frequency be? What meaning do the terms period and frequency have as applied to the wave?

Q11 Describe how you might produce an unpolarized wave in a rope.

13.6 Longitudinal Waves in Air: Sound Waves

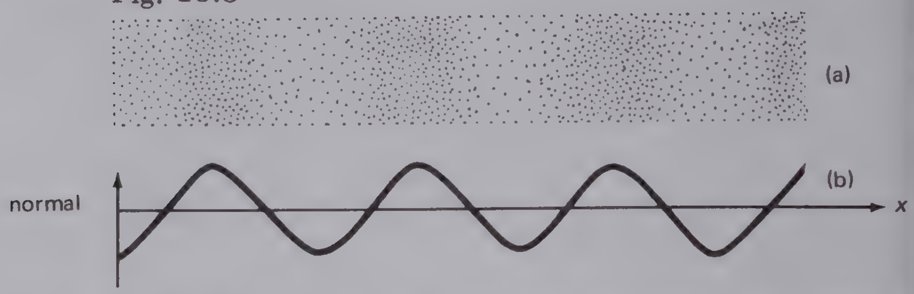
When a tuning fork is struck, the prongs of the fork vibrate back and forth rapidly. As the prongs move outward from their initial position, they push together molecules of the air, creating a compression region in the air. This compression propagates through the air away from the fork much like the compressed coils of a spring do. As the prongs move inward toward each

Activity 13.2, *Vibrations of a Tuning Fork.*

other, a region of lower than normal density of molecules of the air remains where the prongs were. This is a rarefaction, and it propagates away from the fork, following after the compression. Since the prongs of any one tuning fork vibrate at a fixed frequency, the result of their vibration is a longitudinal wave which propagates out through the air. When these compressions and rarefactions strike the human ear, they set the eardrum into vibration at the same frequency as the source. The result is the sensation we call sound.

It is often useful to visualize a longitudinal wave by plotting a graph of the density of particles of the medium against distance along the medium. Such a plot is shown in Fig. 13.8.

Fig. 13.8



(a) "Snapshot" representation of a sound wave progressing to the right. The dots represent the density of air molecules.

(b) Graph of air pressure (P) vs position (x) at the instand of snapshot

The definitions of particles in phase and in opposite phase, of wave amplitude, wavelength, period, and frequency that we gave for transverse waves hold true for longitudinal waves as well. A longitudinal wave, however, cannot be polarized in several planes as a transverse wave can, since the displacements of particles of a longitudinal wave can only be in one direction, the direction in which the wave travels.

In the apparatus arrangement in Fig. 13.9, the amount of sound energy received by the microphone controls the brightness of the light bulb. This light exposes a photographic film and we are able to see a visual record of the distribution of sound energy.

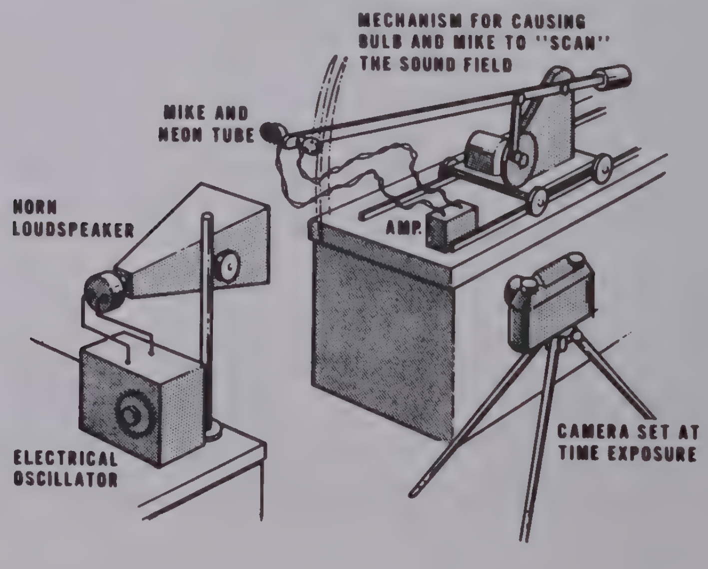


Fig. 13.9

A single microphone-light combination "scanning" an area of interest can record on film the space pattern of sound intensity generated by a horn loudspeaker.

A sound source such as the loudspeaker in the diagram produces longitudinal waves in the air. These waves are detected with the microphone-light bulb combination. The microphone is connected to the light bulb in such a way that loud sounds cause the bulb to glow brightly, softer sounds reduce the light intensity. To show the variations in sound intensity, the microphone and light bulb are rapidly moved up and down and back and forth through the region in front of the speaker. If this is done in the dark, with the camera shutter remaining open, the film will record as bright areas, those regions where the sound is weak. Fig. 13.10 is a picture taken with this apparatus of the sound-wave pattern around a horn type, speaker enclosure.

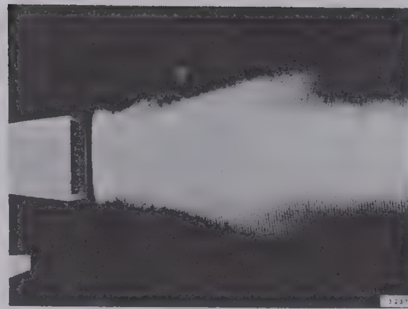


Fig. 13.10

The pattern of sound intensity caused by the pyramidal horn loudspeaker on the left can be portrayed visually with the apparatus of Fig. 13.9. The horn has a six-inch-square aperture; the sound waves being radiated have a frequency of 9000 cycles per second.

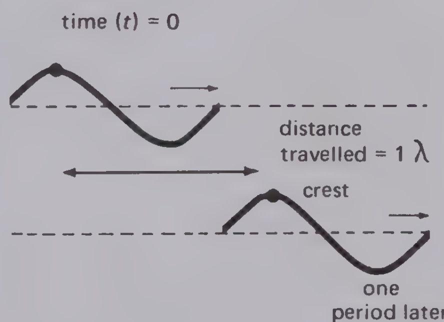
*Q12 Imagine 8 or 10 students from your class standing shoulder to shoulder in a straight line with about 10 cm between each pair. Can you suggest a way to have them simulate a longitudinal wave passing down the line?

13.7 The Universal Wave Equation

If we fix our attention on the motion of any one crest or trough as it propagates through a medium, we notice that the wave travels at a definite speed. This speed is always the same for any one medium, no matter what the wave's frequency or length may be and is determined by certain properties of the medium. The application of simple kinematics gives us a useful way to express the relationship between a wave's speed and its frequency and wavelength.

The average speed of a body is equal to the distance travelled divided by the time taken to travel that distance.

$$v = \frac{d}{t}.$$



Let us apply this relationship to the progress of a wave through a medium. Imagine that a wave crest has moved a distance equal to one wavelength (λ) of the wave. This must take a time equal to one period (T) of the wave. Thus, for any wave, no matter what medium it is travelling in, we can say that its average speed is equal to

$$v = \frac{d}{t} = \frac{\lambda}{T}.$$

But, since $f = \frac{1}{T}$

Then $v = f\lambda.$

This relation is called the **universal wave equation** because it applies to all kinds of waves travelling at any speed whatever, in any medium. For any given medium, the product of the frequency and wavelength of the wave is a constant equal to the speed of the wave. Remember, the speed of the wave is determined by properties of the medium, not by the source. The

source determines the frequency of the wave, and thereby determines the wavelength of the wave. Doubling the frequency of the source results in a halving of the length of the waves. Tripling the frequency decreases the wavelength by one-third. The wave speed is not affected in either case.

Q13 A vibratory source of frequency 20 Hz, produces waves in a medium which supports a wave speed of 60 cm/s. Determine the wavelength of the waves in the medium.

*Q14 Make up a question of your own to illustrate the use of the universal wave equation.

Q15 Why must the universal wave equation hold true for any kind of periodic wave?

13.8 How Fast Does a Wave Travel?

To see which physical factors determine the speed of a wave, let us consider the behaviour of waves in coiled springs. If we produce a wave with a certain frequency and amplitude in one coil, and change either the frequency or the amplitude of the wave there will be no change in the speed of the wave. But, if we stretch the spring, so that the tension is increased, we will see that the wave travels faster. Also, if we produce waves with identical frequencies and amplitudes in two different springs, one made of denser material than the other, we will see that the speed is slower in the denser medium. Thus, the factors that determine the speed of a wave involve properties of the wave medium itself.

For sound waves travelling in air, the property that governs the speed is the temperature of the air. The speed of sound is 332 metres per second at 0° Celsius and increases by 0.6 metres per second for each Celsius degree increase in temperature. Sound waves generally travel faster in liquids than in gases, and faster still in solids.

For waves travelling in shallow water, the property governing the wave speed is the depth of the medium. Waves travel more slowly as the depth of water decreases.

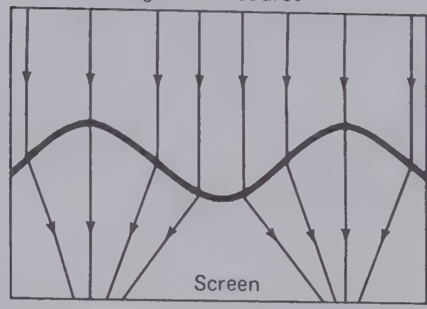
In every case, it is certain properties of the medium which determine the actual propagation speed of a wave. The universal wave equation reveals only that the wavelength of a wave in a given medium is determined by the frequency of the source causing the waves, and allows the calculation of wave speed when its wavelength and frequency are known.

$$\lambda = \frac{v \longleftarrow \text{determined by properties of the medium}}{f \longleftarrow \text{determined by the source}}$$

Q16 a) A wave in a coiled spring travels at 10 cm/s. The frequency of the wave is 2 Hz. Calculate the wavelength of the wave.

b) If the frequency of the wave is doubled to 4 Hz does the wavespeed change? What would occur if the frequency were reduced to 1 Hz?

13.9 The Ripple Tank



A useful method of studying further the properties of waves is to observe surface waves of water. Two or three centimetres of water in a shallow glass tank can be illuminated from above with a light source. Waves can be generated at the surface of the water by moving a point source up and down at the water's surface. Waves propagate along the surface of the water and the crests and troughs of the waves cast shadows on a screen placed underneath the tank. Such an arrangement is called a ripple tank, and is pictured in Fig. 13.11.

Fig. 13.11 A ripple tank

The ripple tank shown in the photograph at the left is being used by students to observe a circular pulse spreading over a thin layer of water. When a vibrating point source is immersed at the centre of the tank, it produces periodic wave trains of crests and troughs.

Considering the motion of any very small segment of the advancing wave front reveals that the direction of propagation of advancing wave fronts is perpendicular to the wave front. Lines drawn perpendicular to the wave front indicate the direction of propagation of the wave at a given point and are called *wave rays*.

By using a long straight rod instead of a point source, straight wave fronts can be produced. Along a straight wave front the rays are parallel to each other. The constant spacing between wave crests is an indication that the waves progress along the tank at a constant speed.

Fig. 13.12 Periodic circular waves.

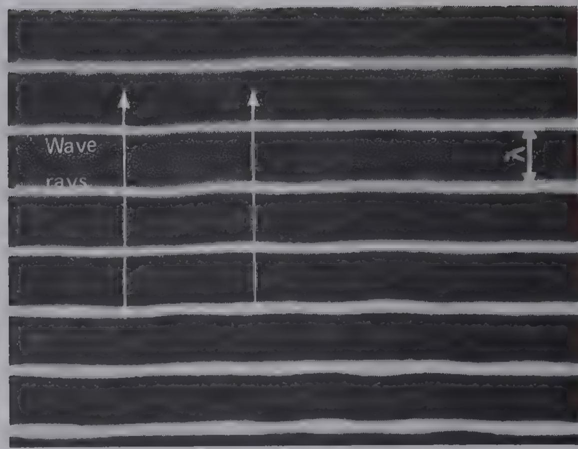


Fig. 13.13

In ripple tanks the wavelength of the wave is often about the same as the depth of the water, and the propagation speed of the wave is determined by the depth of the water.

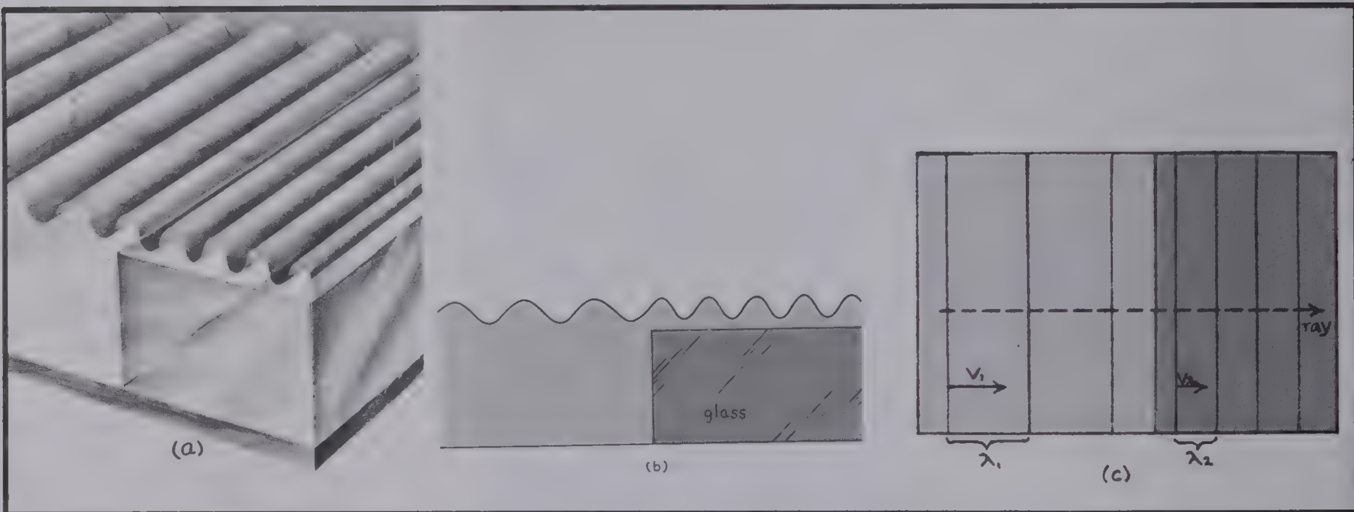


Fig. 13.14

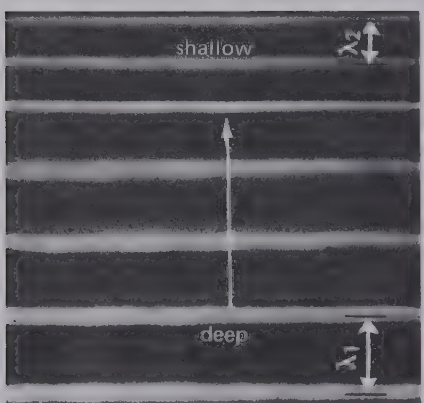


Fig. 13.15

Passage of waves from deep to shallow water. The deep water is at the bottom and the shallow water at the top of the picture.

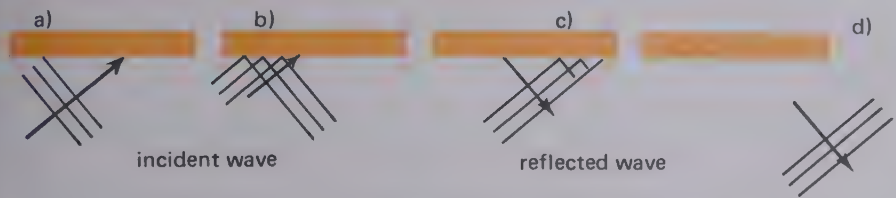
In Fig. 13.14 a glass plate has been placed on the bottom of one region of the tank, producing a shallow section in that region. As Fig. 13.15 shows, the wavelength of waves in the shallow part of the tank is shorter than the wavelength of the same wave series in the deeper part. The frequency of the waves, the number of wave crests passing any point per second, is determined by the frequency of the source, and is the same in both sections of the tank. It is the speed of the waves that decreases as the water depth decreases.

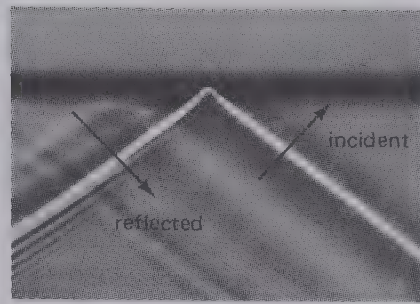
Q17 What is meant by a wave ray?

Q18 The vibrator in a ripple tank produces one new crest each 0.2 seconds. The wavelength of the waves is found to be 3.0 centimetres. What is the speed of the wave?

13.10 Reflection

If we allow a straight wave front to collide with a straight barrier, we see the wave reflect from the barrier.



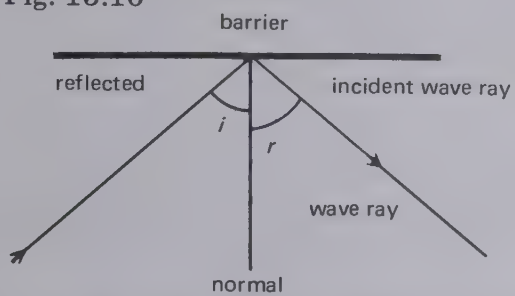


Compare this photo with c) at left

Experiment 13.4, *Reflection of Waves.*

To describe the properties of the collision, refer to Fig. 13.16. A line has been drawn at 90° to the barrier. Such a line is called a normal to the barrier. The angle between the incident ray and the normal to the barrier is called the *angle of incidence* (i). The angle between the reflected ray and the normal is called *the angle of reflection* (r). We can see from the stroboscope photograph that the angle of incidence is equal to the angle of reflection. This equality holds no matter what angle of incidence occurs. The fact that, *the angle of incidence equals the angle of reflection*, is called the **law of reflection.**

Fig. 13.16



In Fig. 13.17, a circular wave front strikes a plane barrier. The sketches below the figure show the path of some of the rays that could be drawn to represent the motion of the waves. In each case, the angle of incidence for a given ray is equal to the angle of reflection of that ray. We can describe the overall effect of this type of reflection without specific reference to rays or the law of reflection if we wish. Notice that the circular reflected waves appear to originate at a nonexistent source S' that lies as far behind the barrier as S does in front of the barrier. This imaginary source S' is called the image of the source S.

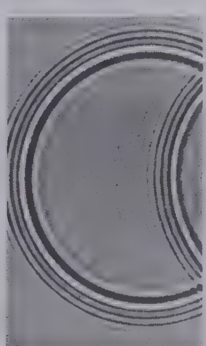
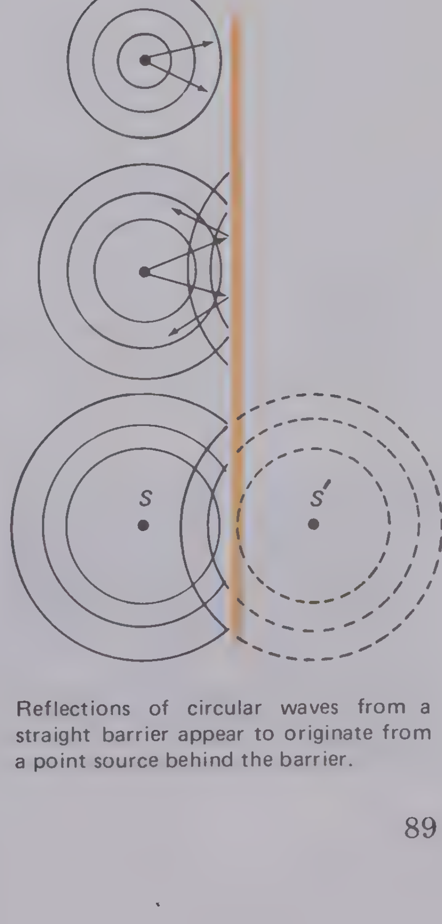
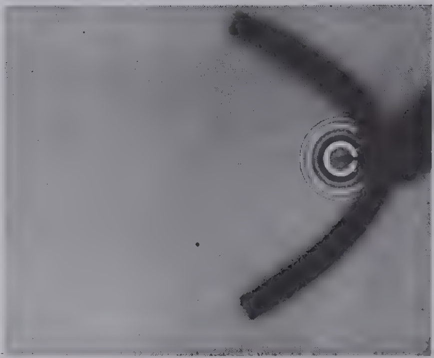


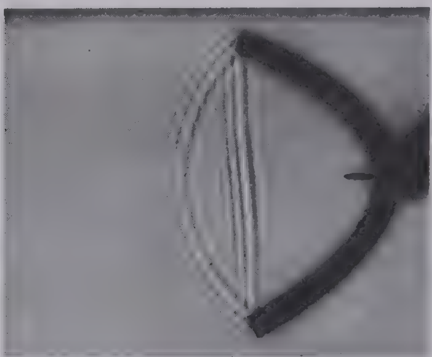
Fig. 13.17



Reflections of circular waves from a straight barrier appear to originate from a point source behind the barrier.

Many kinds of wave reflectors are in use today, for example in radar antennae and infrared heaters. Fig. 13.18 (a) and (b) show how straight line waves reflect from two curved reflectors. A few incident and reflected rays are shown. (The dotted lines have been drawn perpendicular to the barrier surface.) While rays reflected from the half circle are headed off in all directions, a barrier with the shape of a parabola focuses straight line waves precisely at a point. Similarly, a parabolic surface (such as would be produced by rotating a parabola around its axis) reflects plane waves to a sharp focus. An impressive example is a radio telescope, in which a huge parabolic surface reflects faint radio waves from space to focus on a detector at the focus of the dish.





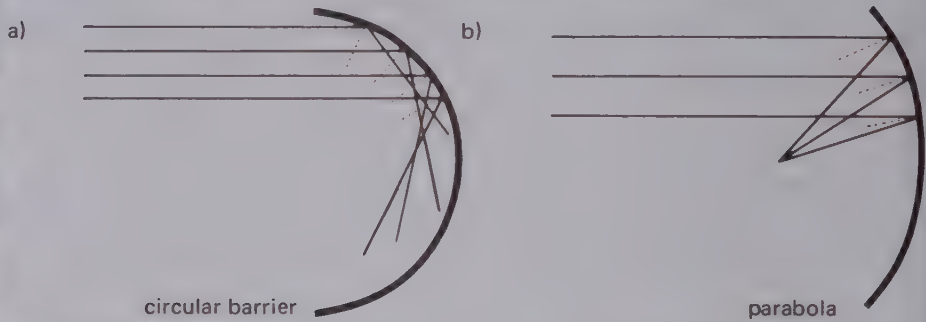


Fig. 13. 18

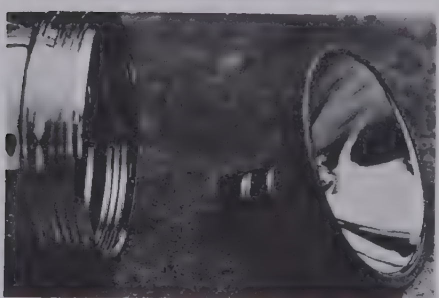
The reflection of parallel wave fronts from circular and parabolic boundaries.

The wave paths indicated in the ray sketches could just as well be reversed. For example, spherical waves produced at the focus will become plane waves on reflection from a parabolic surface. The flashlight and the automobile headlamp are familiar practical applications of this principle, in which white-hot wires placed at the focus of parabolic reflectors produce almost parallel beams of light.

Above: A ripple tank shadow showing how circular waves produced at the focus of a parabolic wall are reflected from the wall into straight waves.

Side: the parabolic surface of a radio telescope reflects radio waves from space to a detector supported at the focus.

Below: the filament of a flashlight bulb is at the focus of a parabolic mirror, so the reflected light forms a nearly parallel beam.



Sound also behaves in a manner consistent with wave reflection properties. An experiment to check if sound obeys the law of reflection can be done by holding a watch at one end of a tube about 50 cm long directed at the wall or some hard object. Prevent sound of the watch from reaching your ear directly by blocking the sound with a barrier. Then listen with a second tube for sound reflected from the wall. The reflected sound is most clearly heard when $\angle i = \angle r$.

Echoes are heard when sound reflects off surfaces that are angled so that part of the original sound returns to the listener.

Sometimes the focusing effect of shapes such as the ellipse of Fig. 13.19 have been unexpected results of architectural design. The Cathedral in the Sicilian town of Agrigento has become famous for the unusual acoustics. The slightest whisper spoken at the western entrance can be distinctly heard behind the high altar, almost 100 metres away. The dome of the U.S. Capitol Building is a similar whispering gallery.

Experiment 13.5, *Refraction of Waves.*

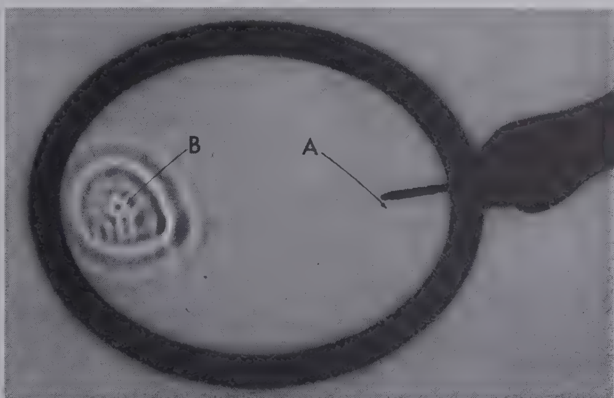


Fig. 13.19 Circular waves produced at focus (*A*) of this elliptical reflector converge to a point at the other focus (*B*), of the ellipse.

Q19 State the law of reflection for waves.

13.11 Refraction

We have already established that the speed with which a wave propagates in a medium is determined by particular properties of that medium. For water waves in a shallow tank the speed is determined by the depth of the water. The deeper the water the greater the speed for waves of any one frequency. When waves travel at an oblique angle from one region into a region where they have a different speed, an important effect, called refraction, is produced.

Activity 13.5, *Moire Patterns.*

Consider the wave front AD moving with a certain speed in the water at the lower edge of Fig. 13.20. The point A on the wave front enters the region of smaller wave speed before points B or C. In the time it takes for C to get to the barrier, A will not have travelled as far as C . A will arrive at A' in the time C gets to

the boundary at C'. The distance AA' depends upon the speed of the wave in the shallow water. Any point between A and D, such as B, will spend more time than A in the higher speed region and consequently will arrive at a point B', when A reaches A'.

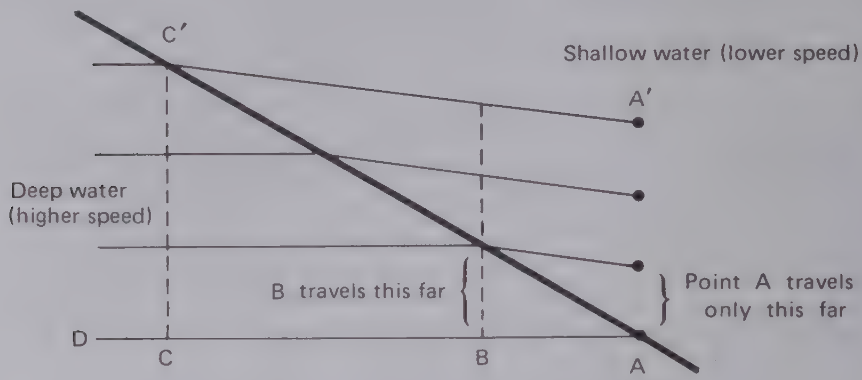


Fig. 13.20 Refraction of plane waves.

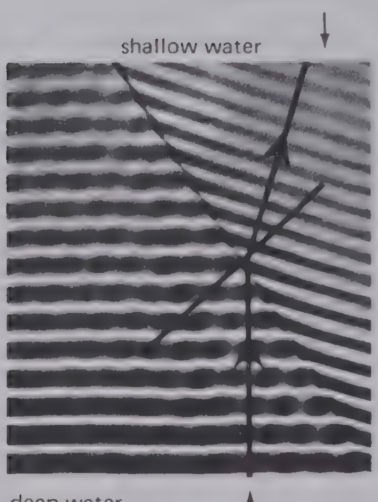


Fig. 13.21
Waves refract toward the normal when they travel from a medium where the wave speed is high into a medium of lower wave speed.

The overall result of this is pictured in Fig. 13.21. The incoming waves change their direction of propagation. This effect is called refraction. Refraction *is the change in direction of a wave as it passes obliquely between regions of differing wave speeds.* The direction in which the bending occurs is usually defined with reference to the path of a *wave ray* rather than to the of the wave front. If the wave travels into a medium in which the wave speed decreases, then the incident ray refracts in the direction toward the normal to the surface drawn at the point where the incident ray strikes the boundary between the media. If the wave travels into a medium in which the wave speed increases, then the refraction occurs in a direction away from the normal.

The problem of how much refraction occurs is determined by the size of the angle of incidence and the ratio of the wave speeds in the two media. This is discussed in more detail in section 13.12.

Sound waves in air propagate at speeds which increase as the temperature increases. This causes refraction when sound waves travel through layers of air at different temperatures. At night, if the air close to a body of water is colder than the air higher up, then the higher sound velocity in the warmer air causes sounds to refract down toward the water. During the afternoon, when the air close to the water has warmed, little or no refraction occurs.

This knowledge lends support to the claim that "sound carries better at night over the water than it does in the daytime".

Q20 Make a diagram to show why wave rays refract *away* from the normal at a boundary of two media where the wave speed *increases* in the second medium.

Q21 What changes in wave speed produce refraction in the direction
a) toward the normal?
b) away from the normal?

13.12 The Law of Refraction

Waves of any kind always refract when they travel at an oblique angle from one medium into another medium in which the wave speed is different. It is possible to derive an exact relationship between the amount of refraction that occurs and the wave speeds in the different media. This relationship is derived below. The result will take on a special significance in Chapter 15.

In the diagram, straight wave fronts are shown proceeding up the page in medium 1 and refracting when they enter medium 2.

Part I Definition of Angles

The angle between an incident "ray" and a normal to the surface, is the angle of incidence i, and the angle between the refracted ray and the normal, the angle of refraction, R. These angles are marked in Fig. 13.23. It is convenient for this derivation to refer to the angle i', the angle between the incident wave front and the boundary, and the angle R', the angle between the refracted wave front and the boundary.

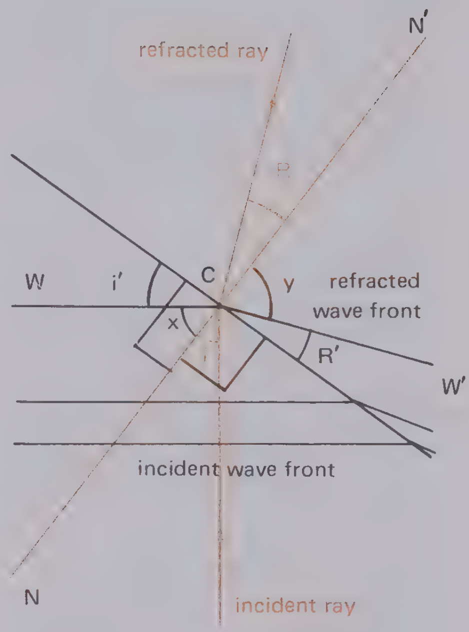


Fig. 13.23

Call angle NCW, angle x.
Notice that $\angle i + \angle x = 90°$
and that $\angle i' + \angle x = 90°$
$\therefore\ \angle i' = \angle i$.
Also, call angle $N'\ CW'$, angle y.
Then $\angle R + \angle y = 90°$
and $\angle R' + \angle y = 90°$
$\therefore\ \angle R' = \angle R$.

Thus, we see that any relationship between $\angle i'$ and $\angle R'$ will hold true for angles i and R as well.

Part II The Refraction Law

Now, let us refer to Fig. 13.24.

In refraction, the relationship between the angle of incidence and refraction is expressed in terms of the sines of those angles, not the angles themselves.

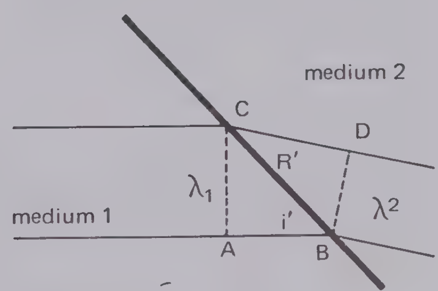


Fig. 13.24

$$\sin i' = \frac{AC}{BC} = \frac{\lambda_{\text{medium}_1}}{BC}$$

and

$$\sin R' = \frac{DB}{BC} = \frac{\lambda_{\text{medium}_2}}{BC}$$

Let us divide equation 1 by equation 2.

$$\frac{\sin i'}{\sin R'} = \frac{\dfrac{\lambda_{\text{medium}_1}}{BC}}{\dfrac{\lambda_{\text{medium}_2}}{BC}} = \frac{\lambda_1}{\lambda_2}$$

But $\lambda_1 = \dfrac{v_1}{f_1}$ and $\lambda_2 = \dfrac{v_2}{f_2}$

and $\angle i' = \angle i$ and $\angle R' = \angle R$.

Therefore $\dfrac{\sin i}{\sin R} = \dfrac{\dfrac{v_1}{f_1}}{\dfrac{v_2}{f_2}} = \dfrac{v_1}{v_2}$ since frequency must be the same in both media.

Since the ratio v_1/v_2 is constant for any two given media, we can write that:

$$\frac{\sin i}{\sin R} = \text{a constant.}$$

This constant is called the *index of refraction* for waves going from medium 1 to medium 2. It is designated by the symbol n_{12}.

$$\therefore \quad \frac{\sin i}{\sin R} = n_{12} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}.$$

Q22 A periodic ripple-tank wave passes through a straight boundary between deep and shallow water. The angle of incidence at the boundary is 45° and the angle of refraction is 30°. Find the index of refraction for waves going from deep to shallow water.

Q23 The speed of water waves in a deep region of a ripple-tank is .30 m/s. The waves enter a shallow region at an angle of incidence of 40°, and then move with a speed of .20 m/s. Calculate

a) the index of refraction,
b) the angle of refraction.

13.13 Diffraction

We have seen that waves travel in straight lines unless they are reflected or refracted. Another way to change the direction of waves is shown in Fig. 13.25. The straight wave fronts in picture (a) pass through an opening that is many times wider than the wavelengths of the waves. They pass through almost without being affected by the slit. As we examine the photographs from (a) through (d), the waves assume a definite circular shape after passing through the slit. In picture (d) where the wavelength of the wave is about the same size as the slit itself, this "spreading" of the straight waves is most noticeable.

The spreading of waves around a corner is called *diffraction*. As Fig. 13.25 reveals, the amount of diffraction depends on the relationship between the wavelength of the wave and the size of the opening. The diffraction effect is greatest when the width of the opening is smaller than the wavelength of the wave. The effect is least when the width of the opening is much larger than the wavelength.

Diffraction effects are produced as waves meet barriers as well as slits. Long ocean swell will diffract around thin ocean pilings almost as if the barrier were not there.

Most audible sounds around the house have frequencies between 200 to 2000 Hz, and therefore wavelengths between 170 and 17 cm. Diffraction should occur then, as sound waves encounter objects and openings found in a typical house, with the effect being most noticeable with long wavelength, low pitch sounds.

Fig. 13.27 a photograph taken using the same technique as was discussed in section 13.6 provides confirmation of the diffraction of sound waves.

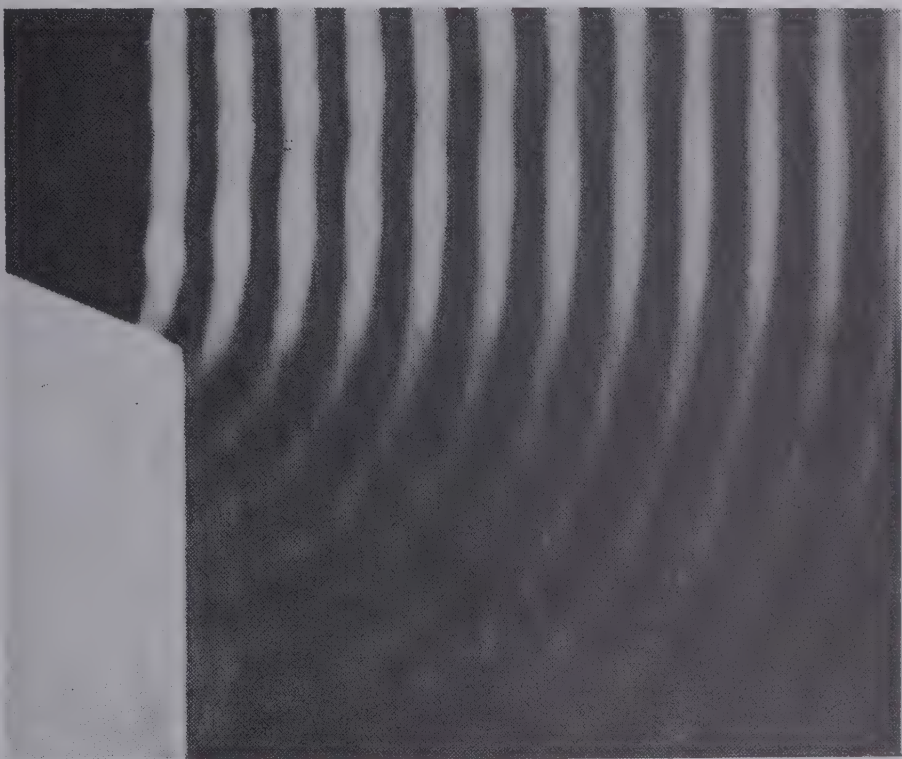
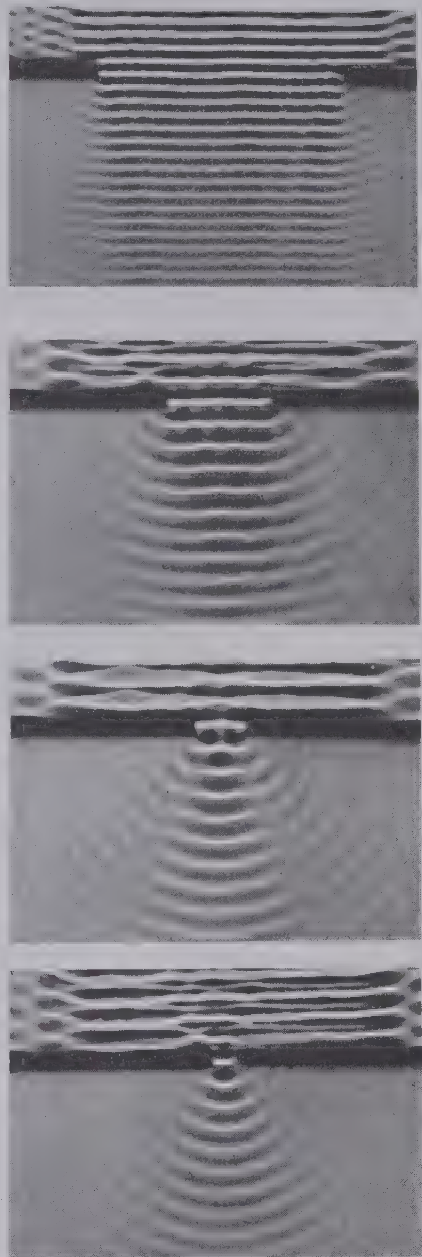


Fig. 13.27

Fig. 13.25



The diffraction produced at a slit depends on the ratio $\frac{\text{wavelength of wave}}{\text{width of opening}}$. Note that the wavelength, frequency, and speed of the wave remain unchanged. The energy of the incident wave becomes spread out over a larger region.

We can account for diffraction if we understand a characteristic of waves, first enunciated by Christian Huygens in 1678, and now known as Huygens' principle.

Huygens' principle, as it is generally stated today, is that *every point on wave front may be considered to behave as a point source for new waves generated in the direction of the wave's propagation.* As Huygens said:

> There is the further consideration in the emanation of these waves, that each particle of matter in which a wave spreads, ought not to communicate its motion [energy] only to the next particle which is in the straight line drawn from the (source) but that it also imparts some of it necessarily to all others which touch it. So it arises that around each particle there is made a wave of which that particle is the centre.

The patterns due to diffraction seen at a slit in a barrier or at the end of a barrier are consistent with Huygens' principle. The wave arriving at the barrier causes the water in the slit to oscillate. The oscillation of the water in the slit acts as a source for waves travelling out from it in all directions.

The behaviour of water at the breakwater wall in the aerial photograph of the harbour below is also consistent with Huygens' principle: water oscillation near the ends of the breakwater is the source of circular waves propagating into the "shadow" region.

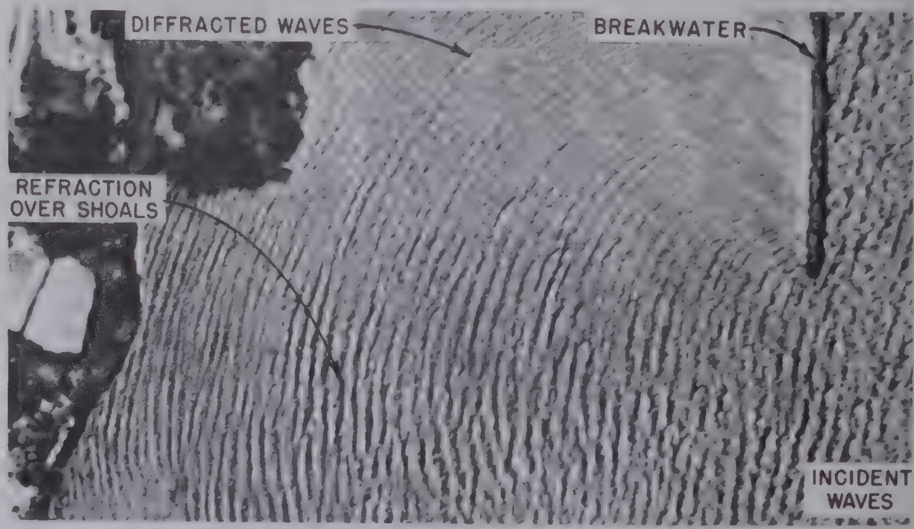


Fig. 13.29 Aerial view of wave effects occurring in the sea.

Q24 State Huygens' principle.

Q25 How can Huygens' principle account for wave diffraction at a slit?

Q26 Plane waves propagate along a ripple-tank as straight wave fronts. Use sketches to show that Huygens' principle is consistent with this observation.

So far we have considered single waves in isolation from other waves. What happens when two waves encounter each other in the same medium? Suppose that two waves approach each other on a rope, one travelling to the right and the other to the left. The series of sketches in Fig. 13.30 shows what happens. The waves pass through each other without either being permanently modified.

After the encounter, each wave shape looks just as it did before, and is travelling along just as it was before. This phenomenon of passing through each other unchanged is common to all types of waves. You can easily see that it is true for surface ripples on water. You could infer that it must be true for sound waves by recalling that two conversations can take place across a table without either distorting the other.

But what is going on during the time when the two waves overlap? They add up. At each instant the rope's displacement at each point in the overlap is just the sum of the displacements that would be caused by each of the two waves alone. If two waves travel toward each other on a rope, one having a maximum displacement of 1 cm upward and the other a maximum displacement of 2 cm upward, the total maximum upward displacement of the rope while these two waves pass each other is 3 cm. We say the two waves have experienced *interference*. In this example, the rope's displacement in the overlap region is greater than that caused by either wave individually. This is called *constructive interference*.

What a wonderfully simple behaviour, and how easy it makes everything! Each wave proceeds along the rope making its own particular contribution to the rope's displacement no matter what any other wave may be doing. If we want to know what the rope looks like at any instant, all we need do is add up the *displacements due to each wave at each point along the rope*. We say that waves obey **a principle of superposition of displacements.**

Another case of wave superposition is shown in the margin. Notice that when the displacements are in opposite directions, they tend to cancel each other. This still fits the addition rule, since one direction of displacement is considered negative and the other positive. This time, the rope displacement in the overlap region is smaller than that caused by either wave alone. This is called *destructive interference*. Notice that in this example, the point P remains undisturbed, *a point of continuous zero amplitude of displacement*. Such a point is called a **node**. A node will occur at one point in the medium whenever two identical waves in opposite phase meet.

The superposition principle applies no matter how many separate waves of disturbance are present in the medium. The examples shown in Figs. 13.30 and 13.31 illustrate the principle applied when only two waves are present, but we can discover by experiment that the superposition is just as valid when there are

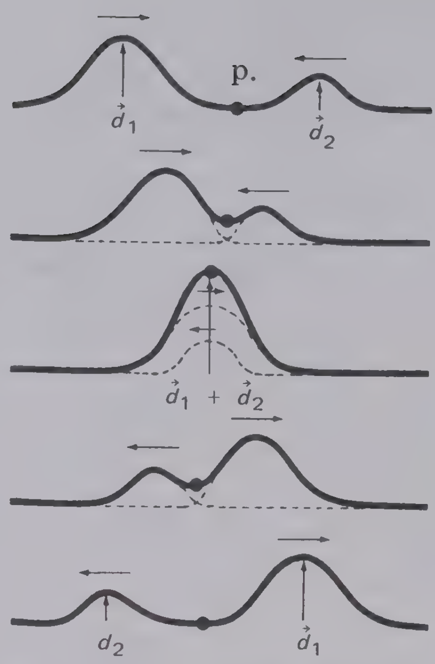


Fig. 13.30 Constructive interference
A superpostiion of two rope waves at a point. The dashed curves are the contributions of the individual waves.

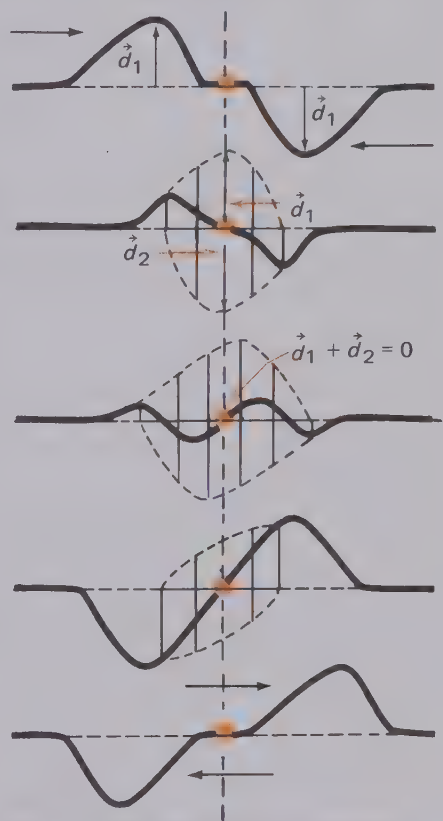


Fig. 13.31 Destructive interference
The principle of superposition of displacements results in the cancellation of one region of a wave by the other wave.

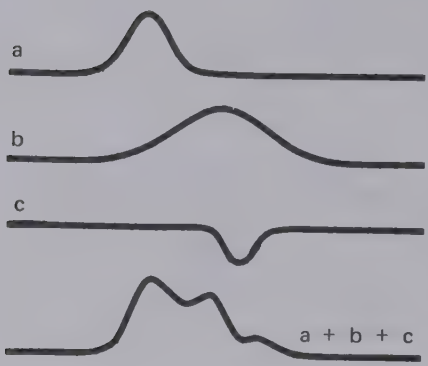


Fig. 13.32

Experiment 13.7, *Interference of Waves.*

three, ten, or any number of waves. Each wave makes its own contribution and the net result is simply the sum of all the individual contributions.

This simple additive property of waves permits us to add waves graphically. You should check the diagrams with a ruler to see that the net displacement (full line) is just the sum of the individual displacements (dashed lines) in these two cases.

We can turn the superposition principle around. If it is true that waves add as we have described, then we can think of a complex wave as the sum of a set of simpler waves. In Fig. 13.32 at the left, a complex wave has been analysed into a set of three simpler waves.

The French mathematician, Jean-Baptiste Fourier, announced a theorem in 1807 that any periodic oscillation, regardless of its complexity, can be analysed as the sum of a series of simpler regular wave motions. Fourier was interested in the theory of heat, sound, light, and electricity, and his theorem became a basic tool for harmonic analysis in all these studies. Fourier showed the general validity of the superposition principle.

Q27 Two wave pulses have amplitudes of 2 cm and 3 cm in the same direction. What will be the maximum displacement of the particles of the medium as they pass each other?
Q28 State the principle of superposition of displacements.
*Q29 Sketch two examples of waves that would interfere destructively with each other.
Q30 What is a node?

13.15 Two-Source, Interference Pattern

Let us return to our discussion of wave phenomena in the ripple tank. Fig. 13.33a) is a picture of a single point source producing circular wave fronts. Fig. 13.33b) shows the wave pattern produced when a second point source vibrates in the same tank in phase with the first source. This pattern is called a two-source interference pattern. The phenomenon is of great importance in both the practical and theoretical aspects of physics.



Fig. 13.33 a) b)

To understand why this pattern results, let us discuss the wave interactions in a region closer to the sources. Fig. 13.34a) shows the positions of wave crests and troughs from both sources some time after the sources were vibrated for two complete periods. Let us examine the interaction of waves from each source along each of two important lines called nodal and antinodal lines.

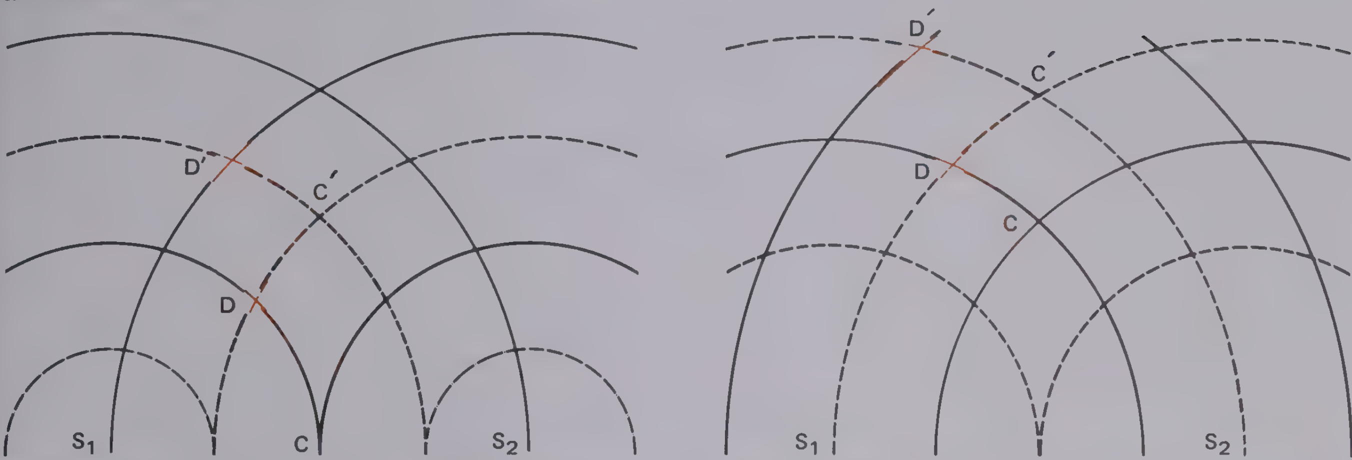


Fig. 13.34 a) At this time, the medium is undisturbed all along the line joining D and D'.

b) One-half period later, each wave has moved, but points along the line joining D and D' remain undisturbed.

Nodal Lines

At D, a crest from S_1 meets a trough from S_2. Applying the superposition principle to this position at this time, we see that there will be complete destructive interference at this point since the waves are in opposite phase. At D', a trough from S_1 meets a crest from S_2, and again, complete destructive interference results. At any point along the line joining D and D', waves from each source also meet in opposite phase, and complete destructive interference is produced along this line.

In Fig. 13.34b) one-half period later, the waves from each source have moved one-half wavelength farther from their respective sources. The waves themselves and the original points of interference, D and D', are now farther away from the sources, but all points along the path followed by D and D' are undisturbed because the two wave amplitudes continue to cancel all along this path. As waves from both sources meet at points lying anywhere along the path followed by D and D', their displacements will continue to cancel each other by complete destructive interference.

Fig. 13.35 shows the pattern produced after the two sources have vibrated through many complete oscillations. We observe several lines of complete destructive interference. These are called nodal lines. They are marked ◒ and labelled N in the diagram. All points along the nodal lines are nodes.

Antinodal Lines

Examining Fig. 13.34a) again, we see that the crests from both sources meet at the point C. Constructive interference will occur at this point, producing what we could call a double crest.

At C', the troughs from each source meet and will interfere constructively producing a double trough. Points along the line between C and C', although they are not double crests or double troughs, are displaced up or down more than they would be due to either wave alone, and therefore they are all points at which constructive interference occurs. Fig. 13.34b) indicates that as the waves move out from each source, the double crests and troughs move outward along the line between C and C'.

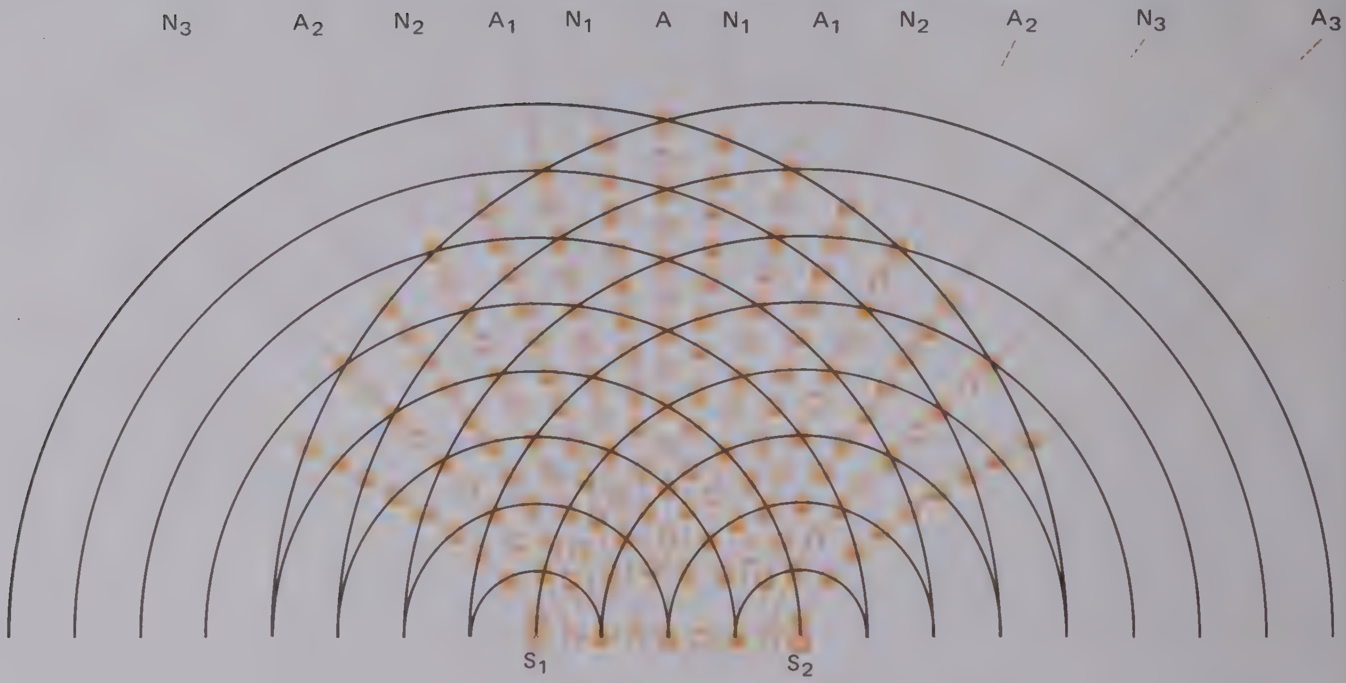


Fig. 13.35

Reference to the full pattern shown in Fig. 13.35 reveals several such lines along which maximum constructive interference occurs at all times. Such lines are called antinodal lines. The positions marked O and ● are positions where double crests and double troughs are located at this instant of time. These positions will move outward along the antinodal lines as time elapses.

You should compare Fig. 13.35 with the picture in Fig. 13.33b) to make sure you know which are the nodal lines and which are the antinodal lines in the ripple-tank photograph.

Using the Interference Pattern

The ability to locate the nodal and antinodal lines in an interference pattern enables us to compute the wavelength of the wave causing the pattern. Locate a point P on the first antinodal line a distance x from the centre antinodal line. If the distance ℓ from this point to a point midway between the sources is much larger than the source separation d, then there is a simple relationship between ℓ, d, x, and λ, the wavelength of the wave.

$$\lambda = \frac{dx}{\ell}\ .$$

This relationship is derived on the next page.

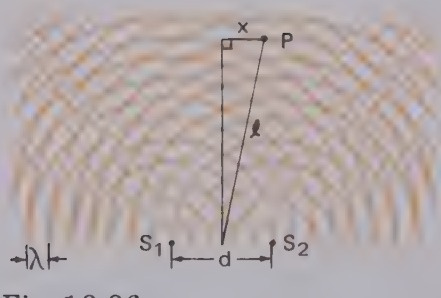


Fig. 13.36

Derivation of Relation for Calculating Wavelengths from an Interference Pattern

This derivation of a formula for calculating the wavelength of waves forming a two source interference pattern is based on making an approximation. The test of the validity of the approximation used will be: does the formula based on the approximation give a reasonable value for the wavelength of the waves? You can check this for yourself by using the formula derived here to calculate the wavelengths of the waves in Fig. 13.33b) or Fig. 13.36 and comparing the answer with the wavelength found by direct measurement from these figures.

Choose a point P, on the first antinodal line from the central antinodal line, and much farther away from the sources than their separation distance, d.

Let:

d = the separation between two point sources of circular waves, S_1 and S_2, that are vibrating in phase, and with the same frequency.

ℓ = the distance from the centre of the sources to point P.

x = the distance from the central antinodal line, OP, to a point P along the detection line.

Waves travelling from S_1 to P must travel one wavelength farther than waves from S_2, since P is on the first antinodal line. Therefore, if an arc is drawn with centre P and radius PS_2 to cut PS_1 at M, then MS_1 is equal to one wavelength of the waves.

If point P is very far away from the sources, then PM and PS_2 are very nearly parallel lines. Since $PM = PS_2$, the triangle PMS_2 is isosceles, and the angle PMS_2 = angle PS_2M. *Now let us say that P is so far away from the sources that we can regard PS_1 as parallel to PS_2.* Then the sum of angles PMS_2 *and* PS_2M is very nearly 180°. Therefore, each angle is very nearly 90°.

Then, angle PMS_2 = angle $PS_2M = 90^\circ$

and, angle MS_1S_2 = angle POS_2. Call these angles "a"

and, angle QPO = angle POS_2 = angle "a"

Therefore, in triangles PQO and S_1S_2M,

angle PQO = angle $S_1MS_2 = 90^\circ$

angle MS_1S_2 = angle QPO = angle "a".

Therefore these are similar triangles and we can say that:

$$\frac{MS_1}{S_1S_2} = \frac{QP}{OP}$$

or $$\frac{\lambda}{d} = \frac{x}{\ell}$$

and $$\lambda = \frac{dx}{\ell}$$

If we measure d, x, and ℓ, we can calculate a value for the wavelength.

Fig. 13.37

These angles become more nearly 90° the farther P is away from $S_1 S_2$

Q31 What is the approximation on which this derivation is based?

* Q32 How valid do you feel the formula is?

Using this formula we can measure the wavelength of waves even if we cannot see the waves themselves, by measuring properties of the interference pattern they produce.

There is another dividend to be obtained from the existence of the two-source interference pattern. This pattern is the unique result of the interference properties of waves. Any type of wave should exhibit this pattern where two point sources of waves in the same phase exist side by side. If the energy coming from the sources is in any form other than wave energy, such a pattern will not be formed. Thus, the detection of a two-source, interference pattern provides convincing evidence that the phenomenon producing the pattern is indeed a wave phenomenon.

Activity 13.4, *Thought Problem.*

*Q33 The discussion of the two-source, interference pattern provides an example of how a careful physical and mathematical analysis of a phenomenon can yield results with wide applications. What kind of applications can you foresee?

*Q34 Use the relation $\lambda = \frac{dx}{\ell}$ to calculate the wavelength of the wave in Fig. 13.36. Compare your result with that result obtainable by direct measurement.

3

Handbook

Table of Contents

Preface

The purpose of this handbook is to provide you with some guidance in things which you can do in order to get some first-hand experience with the techniques of scientific investigation and the ideas and concepts of this physics course.

This handbook is different from many other such books in that it contains far more material than you would ever be expected to do in a single course. You will have to choose, with the help of your teacher, experiments and activities which will be the most interesting and useful to you.

For the most part, there is a handbook chapter related to each chapter of the text. In each chapter, there are usually three sub-sections: *Experiments, Activities,* and *Film Loop Notes.*

For each *Experiment,* instructions are outlined fully and may be followed by the entire class. In some cases, alternate procedures are outlined and you may choose one or more on the basis of available equipment or personal preference. At the end of some experiments are *Additional Questions* which may suggest further experimentation with which you could deepen your understanding, or develop additional techniques.

In the *Activities* are suggestions for mini-experiments, exercises, or projects which you can do on your own time. Detailed instructions for the activities are not usually given so that you may develop them by yourself in your own way.

Some film loops are recommended as part of this course. The *Film Loop Notes* provide background about these loops and give instructions for their use.

Keeping Records of Laboratory Work

An essential part of doing laboratory work is the recording of results as the experiment proceeds. It is essential, because later, you or someone else will probably want to know what happened. In this section is some advice on how to keep a good record of your laboratory work. Your teacher may suggest a particular format for your reports, but regardless of the type of record to be kept, there are some general principles which you should always try to follow.

1. Make your report sufficiently clear and complete so that months after its writing you will be able to pick up your report and from it explain to yourself or someone else exactly what happened.

2. Keep a complete record *as you do the experiment!* It is a bad habit to put data on a scrap of paper and then recopy them into your notebook later.

3. As you do the experiment, include in your record, answers to questions which occur to you or are given in the handbook. They are often important to your understanding of what is happening in the experiment.

A complete record usually contains the following parts.

Aim. You should know what you are trying to do before you start the experiment and should write your aim at the top of your report before you begin.

Apparatus. A good way to record what you use is to prepare a sketch of the apparatus. Label the main parts. List the types of equipment and any special settings or adjustments in case you wish to repeat the experiment at a later time.

Procedure. Outline the main points of what was done. Reference to the handbook for a description of the procedure may be adequate in some cases. (Such a reference would save some time.)

Observations. Organize all numerical data, if possible, in tabular form. Always identify the units, (metres, kilograms, seconds, etc.) for all of the data you record. If you suspect that a particular piece of data is not very reliable, (perhaps you measure it too quickly or the apparatus shifted), cross it out and make an explanatory note of the fact. Do not erase the reading. You may find out later that it was correct after all and that you, not the data, were in error.

Analysis. Once you have collected the data you will interpret what they mean. Your analysis is the means by which you arrive at conclusions from your observations. While doing this analysis, do not ask, "What was supposed to happen?". Rather ask, "Based on my observation what must have happened?". In trying to

answer this last question, show all steps of reasoning and calculation clearly.

Include in the analysis, a discussion of sources of error or uncertainty and try to estimate how large each could be. If you want to take this calculation a step further, you could estimate the total uncertainty in your result due to the uncertainties in several separate factors.

Conclusions *Conclusions must be based on your observations.* They should summarize what you learned from the experiment, not what you think "they" want (your teacher, the authors of the text . . . , or whoever). To relate conclusions to specific observations, a good format to use for a statement of a conclusion is, *since . . .* happened, *therefore . . .* must be true.

There is no "wrong" result in any experiment. If your observations and measurements are correct within the limitations of uncertainty, and your analysis is sound, then your results will be correct. Whatever happens in nature, including the laboratory, cannot be "wrong".

Feb. 8, 1974

EXPERIMENT 5.8 FRICTION

AIM: This is an investigation of the effect of mass and contact surface area on the force of friction retarding a wooden block sliding on a flat smooth wooden plank.

APPARATUS: See figure 1 and also p.136 in the handbook for further details.

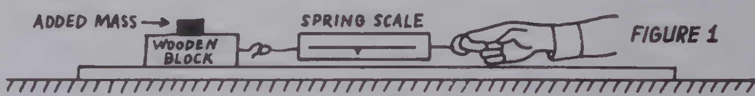


FIGURE 1

PROCEDURE: The minimum force to keep the block moving at constant velocity was measured in several situations. See handbook p.137 for complete procedure.

OBSERVATIONS: mass of block = 183.2 g.

Static and Kinetic Friction: minimum force to start the block = (1.1 ± 0.1) N
minimum force to move block uniformly = (0.8 ± 0.1) N

Effect of Mass: Table 1 shows minimum force F to pull block uniformly with various loads.

Effect of Area: Dimensions of block = 4.2 cm X 8.0 cm X 10.1 cm. Table 2 shows minimum force F required to pull unloaded block on each of its sides.

TABLE 1 EFFECT OF MASS

Mass (g)	F (N)
183.2	0.8 ± 0.1
233.2	0.9 ± 0.1
283.2	1.2 ± 0.1
333.2	1.5 ± 0.1
383.2	1.6 ± 0.1
433.2	1.9 ± 0.1

TABLE 2 EFFECT OF AREA

Side	Area (cm^2)	F (N)
A	80.8	0.8 ± 0.1
B	80.8	0.8 ± 0.1
C	33.6	0.9 ± 0.1
D	33.6	0.8 ± 0.1
E	42.4	0.7 ± 0.1
F	42.4	0.8 ± 0.1

CONCLUSIONS:

1. Since F was applied in each case so that a = o (at rest or constant velocity), the applied force is equal and opposite to the force of friction between the block and the board. (Air resistance is negligable here).
2. Since F is greater when the block is at rest than when moving, static friction must be greater than kinetic friction.
3. Since a plot of F versus mass is linear and passes through (0,0) (See Graph #1 attached), the force of kinetic friction is directly proportional to the mass of the block. This was not investigated for static friction but it seems reasonable that it would be affected similarly.
4. As results in Table 2 indicate, the friction force did not deviate by more than the experimental uncertainty (±0.1N) from the average of F=0.8N. Therefore friction is independent of area of contact.

Chapter 10. Momentum

In our study of Newtonian mechanics we have tried to analyse each event in terms of cause and effect. In other words, each event was considered as an interaction between agent and victim. In the laboratory, collisions between pairs of objects such as steel balls, dynamics carts, or air track gliders, are interactions which can be studied easily.

In the experiments of this chapter, you will study collisions by making measurements *before* and *after* two objects hit each other. The collisions happen too quickly for you to follow what happens *during* the interaction.

What should you measure in order to find a link between the initial and final states of the objects? Are there any quantities which remain unchanged for the two objects before, during, and after their collision? These are the important questions which you should keep in mind as you do the experiments. Answers to these questions apply not only to medium-sized objects such as the dynamics carts, but also to interactions between atomic and sub-atomic particles on the one hand (see the photograph of a cloud chamber in the text, page 10), and interactions between stars and galaxies on the other.

Experiment 10.1 Collisions with Carts 1

In this experiment, you will investigate an easy-to-analyse, head-on collision between two dynamics carts. In each case, one of the carts will be at rest initially, and then, after the collision, the two carts will be stuck together.

Place two dynamics carts on a long, smooth table. (A surface 2.0 metres long is ideal.) If none of your tables are long enough, use the floor. Be sure the surface is free of dirt and that the carts' wheels are well lubricated so that friction is reduced to a minimum. If you are not satisfied, you can compensate for friction by elevating one end of your work surface. When the slope is correct, a cart will move at an almost-constant velocity when given a slight push.

Devise a method for measuring the speed of each cart before and after the collision. Use stopwatches or vibrating timers as you did in Unit 1.

Put two lumps of plasticine on the colliding ends of the carts. This should make the two carts stick together on contact. Place one cart, which we shall refer to as *B*, at the middle of the track. Once you are prepared to measure the speeds of *A* and *B* both before and after the collision, launch *A* to collide with *B*. An initial speed of approximately 1 m/s should work well.

Figure 10.1

If you wish to repeat this experiment keeping the same initial speed for *A*, build a launcher. A simple launcher is an elastic band stretched between two retort stands clamped as shown in Figure 10.2. You can launch the cart several times with the same initial speed by extending the elastic by the same amount for each successive launch. The precision of your results will be improved by averaging data for several trials.

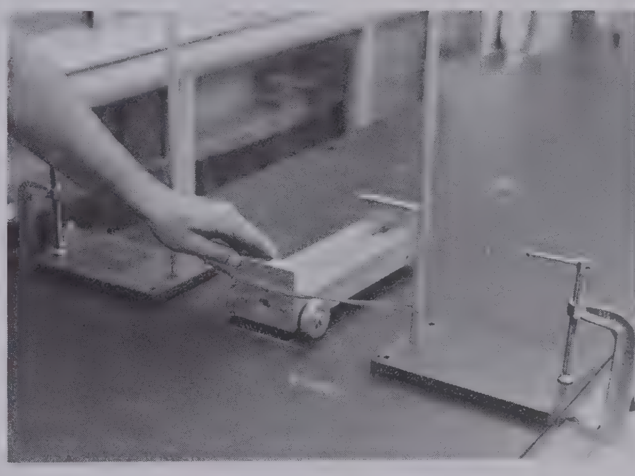


Figure 10.2

Record the masses and the initial and final velocities of each cart in a table similar to Table 10.1. The blank columns will be useful in your analysis.

Table 10.1

Initial State			Final State		
Mass m_A (kg)	Velocity $\vec{v}_A$ (m/s)		Mass $m_A + m_B$ (kg)	Common Velocity $\vec{v}'_A = \vec{v}'_B$ (ms)	
1			1		

Double the mass of B by adding masses or another cart and then repeat the collision. Finally, triple the mass of B and repeat the collision. Tabulate your data.

Analysis

Q1 Why is it desirable to minimize outside forces acting on the carts (such as friction)?

Q2 Is there a quantity which is conserved in all the collisions? From your data, try combinations of m and $\vec{v}$ such as $m + \vec{v}$, $m - \vec{v}$, $m \times \vec{v}$, $m/\vec{v}$, $m^2\vec{v}$, etc.

Experiment 10.2 Collisions with Carts 2

In this experiment, the coupling arrangement is replaced with spring bumpers like the ones shown in Figure 10.3. Measurement and analysis is more difficult here because after the collision, the velocities of the carts will not be equal.

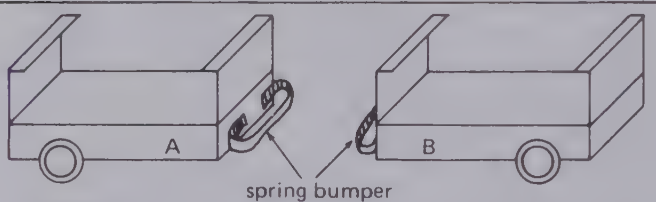


Figure 10.3

Once again, start with cart B at rest and launch A to collide head-on with B. Measure the velocities of A and B before and after the collision. Here, their directions may be different so use a sign convention (+ and –) to indicate in which way the carts travel. To record your data, you will need a table with headings similar to those in Table 10.2. If you have a launcher, repeat your measurements and record an average.

Repeat for other masses by piling bricks or carts on either A or B.

Analysis

Calculate the momentum for each object before and after the collision and tabulate your results. (Use the same sign convention for both momentum and velocity.)

Calculate the initial and final momenta for the system by adding the momenta of A and B.

$$\vec{P}_{total} = \vec{P}_A + \vec{P}_B \qquad \vec{P}'_{total} = \vec{P}'_A + \vec{P}'_B$$

This is a vector addition so the signs are important. Tabulate your results.

Q1 Based on your data, is momentum conserved in these collisions?

Q2 What are the sources of experimental error here?

Q3 What is the percentage difference in $\vec{P}_{total}$ and $\vec{P}'_{total}$?

Additional Questions

Q4 Estimate the experimental uncertainty in your measurements and calculate the percentage uncertainty in $\vec{P}_{total}$ and $\vec{P}'_{total}$ for each case. Is the percentage difference in these values less than the percentage uncertainty in each case? Should it be? Discuss.

Q5 *Vis Viva*. Huygens suggested in 1668 that in collisions between hardwood pendula, another quantity, $m(\vec{v})^2$, was conserved. Leibniz called the quantity $m(\vec{v})^2$, the *vis viva* of an object. Use your experimental data to test Huygens proposed law of conservation of *vis viva.*

Calculate the *vis viva* for each object before and after the collision in the experiment. Extend your table and tabulate the results.

Calculate the total *vis viva* for the system before and after the collision.

Is *vis viva* conserved in the collisions in Experiments 10.1 and 10.2?

Q6 Distinguish between elastic and inelastic collision using examples from Experiments 10.1 and 10.2.

Table 10.2

Mass		Initial State					Final State				
m_A (kg)	m_B (kg)	$\vec{v}_A$ (m/s)	$\vec{v}_B$ (m/s)	$\vec{P}_A$ ( )	$\vec{P}_B$ ( )	$\vec{P}_{tot}$ ( )	$\vec{v}'_A$ ( )	$\vec{v}'_B$ ( )	$\vec{P}'_A$ ( )	$\vec{P}'_B$ ( )	$\vec{P}'_{tot}$ ( )

Experiment 10.3 Collisions with Carts 3

In the previous experiments, you have studied elastic and inelastic collisions in which one of the two objects was initially at rest. If you have time, you should investigate more general types of collisions to see if the same basic principles apply.

Using procedures which you have developed in Experiments 10.1 and 10.2, launch carts to collide head-on, or one into the rear of the other, in cases where both carts are moving before the collision. It will be necessary to repeat each collision several times so that you can measure the velocity of each cart before and after the collision. Use plasticine and spring bumpers to give inelastic and elastic collisions. Record your results in a table like Table 10.2.

Analysis

Calculate the momentum for each cart and the total momentum before and after each collision for which you have obtained data. (Remember these are vector quantities.)

Q1 What are the sources of experimental error here?
Q2 What is the percentage difference in $\vec{P}_{total}$ and $\vec{P}'_{total}$ for each case?
Q3 Was momentum conserved within the range of experimental uncertainty of your measurements? In your discussion show calculations.

Experiment 10.4 Collisions on an Air Track

The air track eliminates much of the undesirable friction, so if one is available you may want to use it instead of the carts to investigate these collisions.

One way to measure velocities of the gliders is shown in Figure 10.4. The velocity of each object can be calculated from the time-intervals during which a card of known length (say 10.0 cm) mounted on the object, interrupts the light beam to the photo diode. Another way to record the motion is with a stroboscopic photograph.

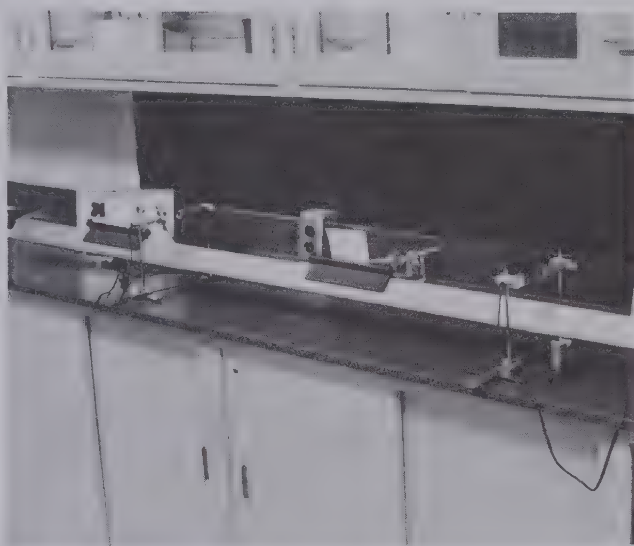


Figure 10.4

To obtain data, follow the procedures outlined in the previous experiments. Then, analyse each case and answer the questions shown.

Q1 What are the sources of experimental error here?
Q2 What is the percentage difference in $\vec{P}_{total}$ and $\vec{P}'_{total}$ for each case?
Q3 Was momentum conserved within the range of experimental uncertainty of your measurements? In your discussion show calculations.

Experiment 10.5 Photographs of Collisions (in One Dimension)

If you were unable to obtain good data for collisions or you wish to look at other examples of collisions of various types, you may use the stroboscopic photographs of collisions which are provided in this experiment.

These photographs show seven different collisions between two steel spheres suspended from long, bifilar wire supports as illustrated in Figure 10.5. The balls swing in a large arc so that they are moving almost in a horizontal straight line before and after the collision. In some events the balls are covered with putty so that they will stick together on contact.

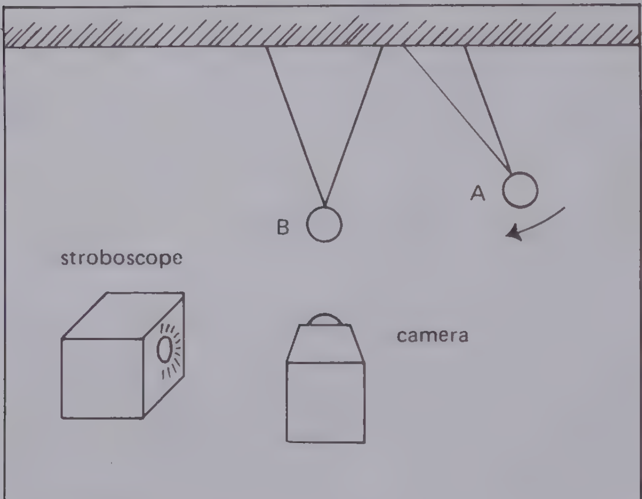


Figure 10.5

Measurement

On each photograph, two reference bars which are 1.00 metres apart are shown. On the photograph, measure the distance between bars for each event you analyse and then, from your data, calculate the magnification factor. For example, if the distance between the bars is 10.0 cm, then the magnification factor is 1.00 m / 10.00 cm = 1.00 m / 0.100 m = 10.

To find a ball's velocity, first measure the distance travelled between flashes. In some cases you can improve your accuracy by measuring several intervals and finding the average. Use the magnification factor to find the actual distance travelled. The flash frequency is 10 flashes/second for each photograph. From this determine the time between flashes. Finally, calculate the magnitude of the ball's velocity.

$$v = \frac{\text{distance travelled between flashes}}{\text{time between flashes}}$$

Record the result in a table and indicate its direction with a sign (+ or −).

Analysis

Calculate the momentum of each ball and the total momentum of the system before and after the collision.

Q1 Based on your data for each event, is momentum conserved?

Q2 For each event, what is the percentage difference in $\vec{P}_{total}$ and $\vec{P}'_{total}$?

Figure 10.6 10 flashes per second $M_A = 532$ g $M_B = 350$ g

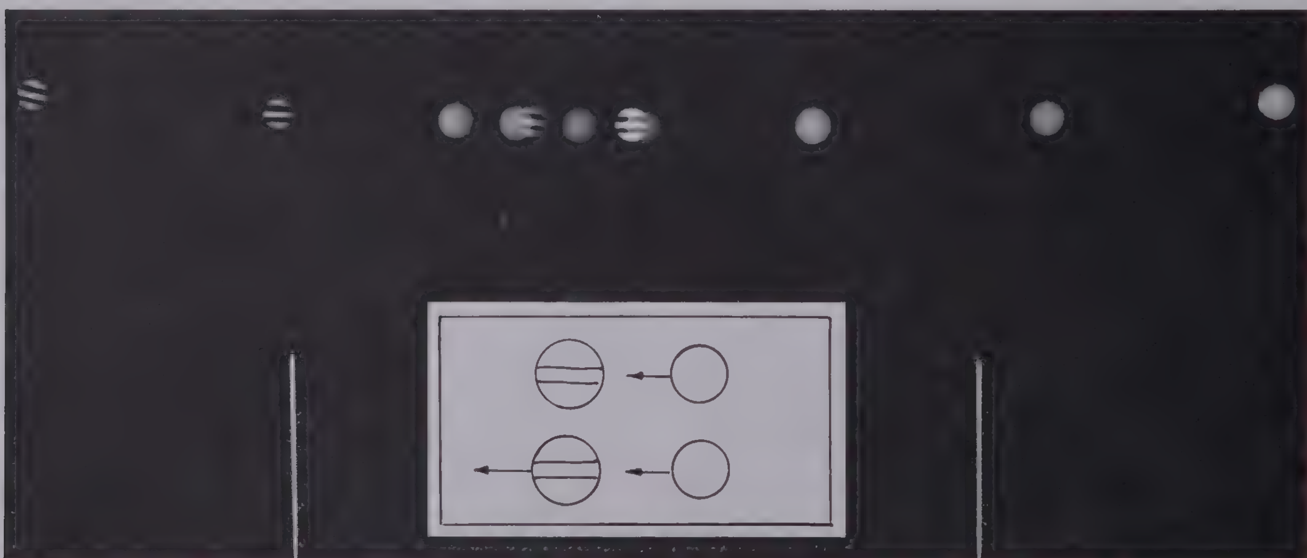
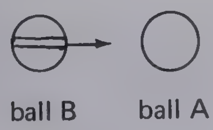


Figure 10.7

10 flashes per second

$M_A = 532$ g $\quad M_B = 350$ g

before



after

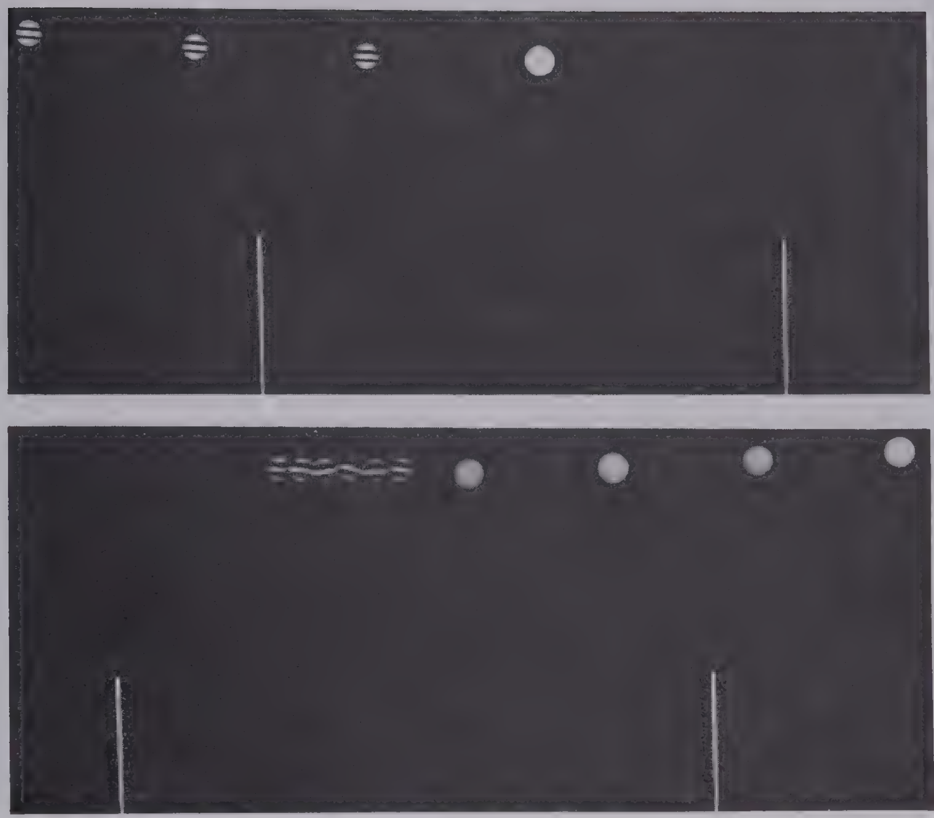
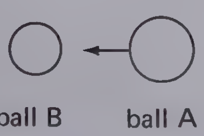


Figure 10.8

10 flashes per second

$M_B = 443$ g $\quad M_A = 662$ g

before

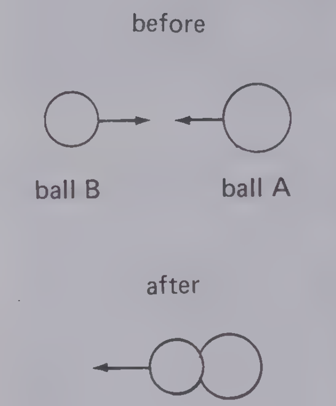


after

Figure 10.9

10 flashes per second

$M_B = 443$ g $\quad M_A = 662$ g



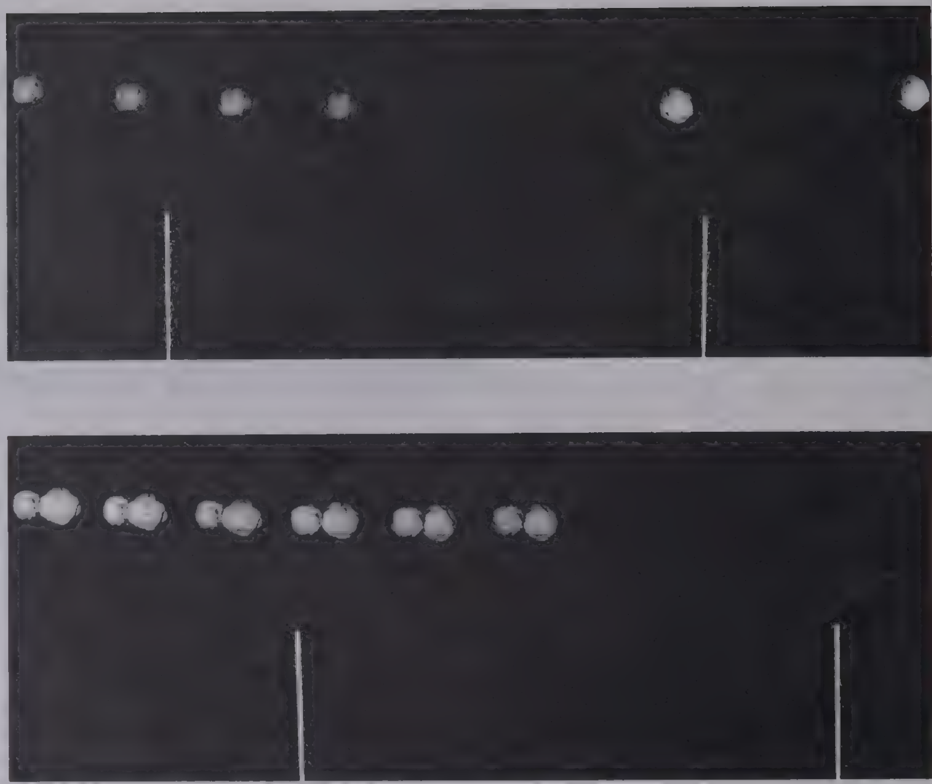
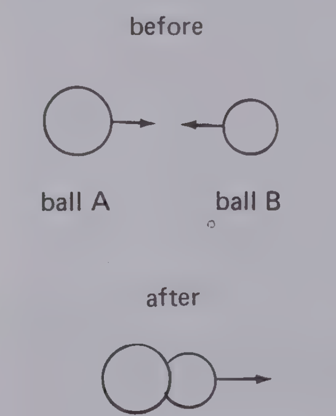


Figure 10.10

10 flashes per second

$M_A = 4.79$ kg $\quad M_B = 660$ g



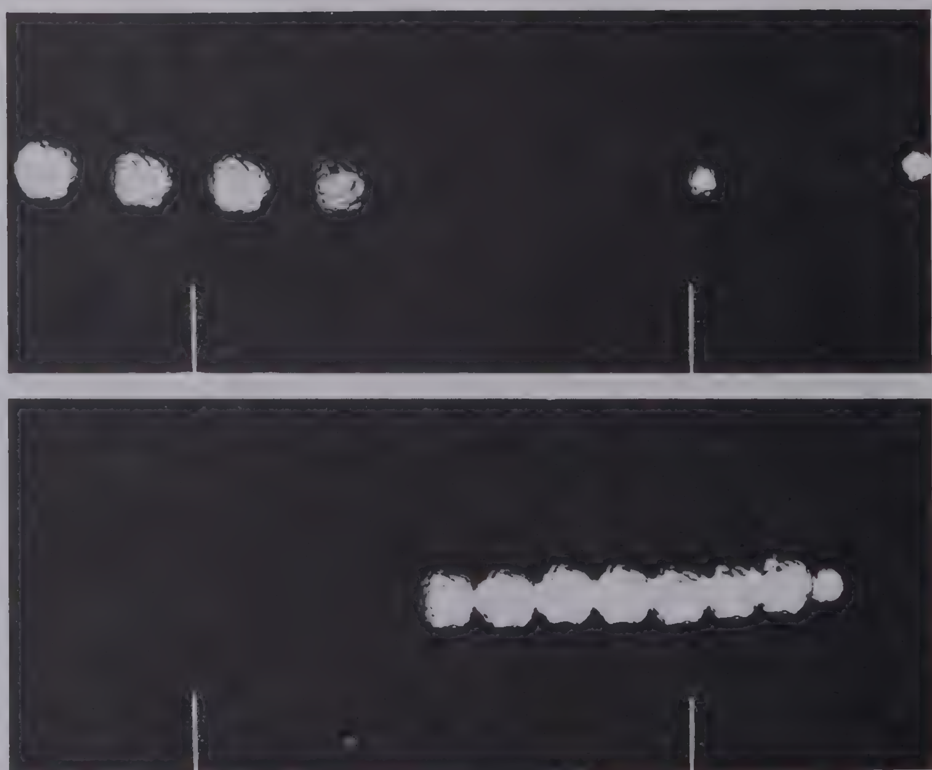


Figure 10.11

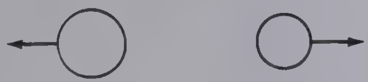
10 flashes per second

$M_A = 1.80$ kg $M_B = 532$ g

before

ball A ball B

after



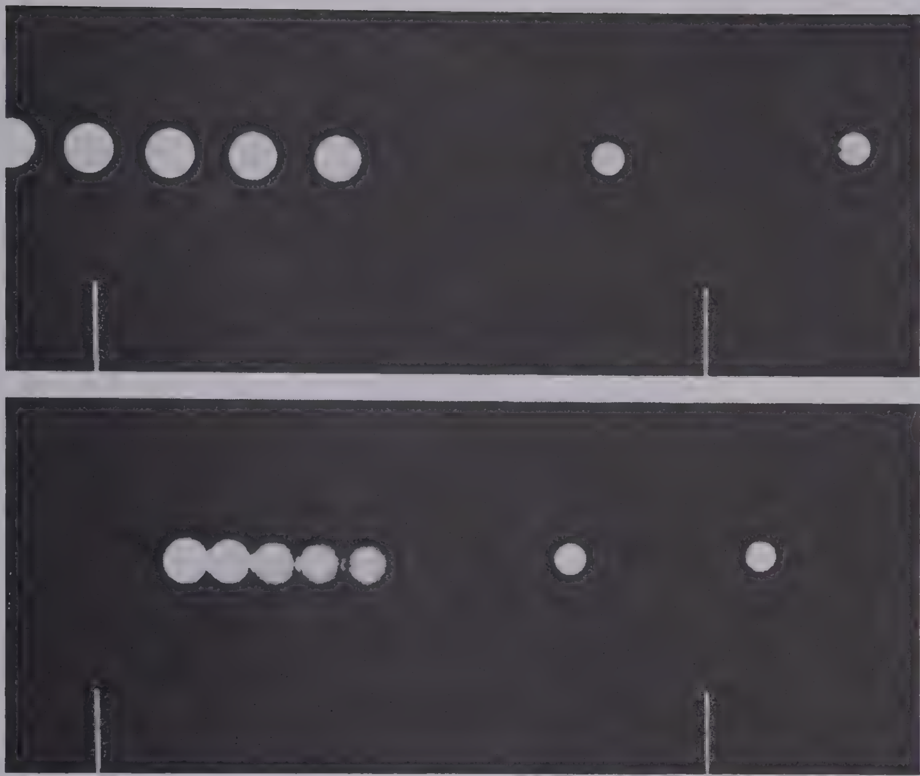


Figure 10.12

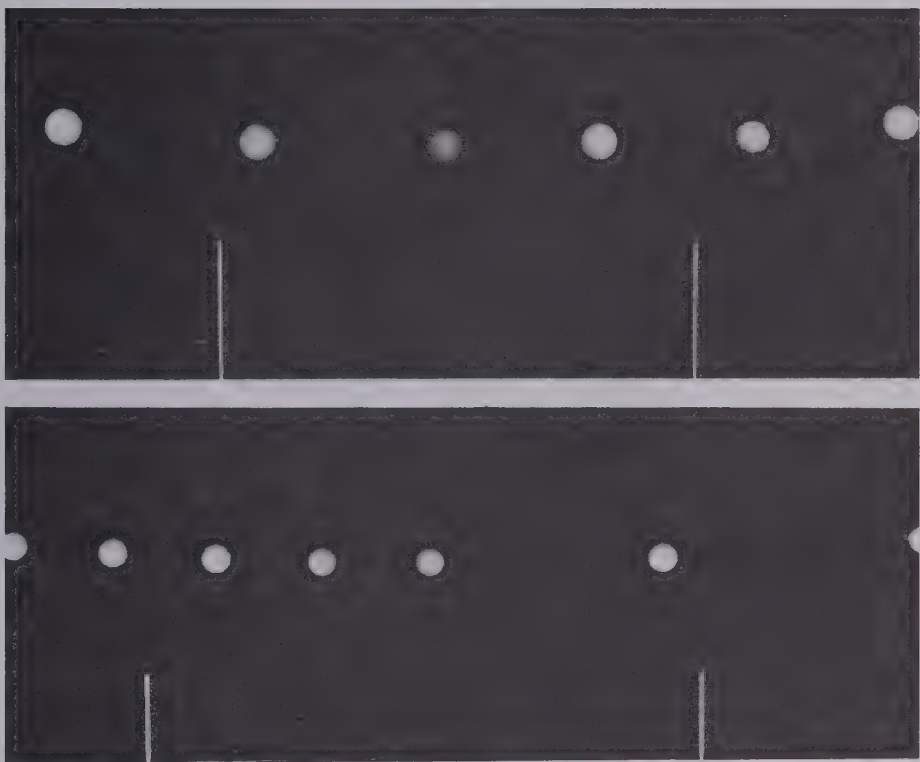
10 flashes per second

$M_A = 1.80$ kg $M_B = 532$ g

before

ball A ball B

after



Experiment 10.6 Collisions in Two Dimensions

Collisions in a straight line, such as you have been investigating, are in one dimension. You can also study collisions in two dimensions by having two objects glance off each other at various angles. This type of collision can be observed between air pucks on a smooth surface, pucks on an air table, or pucks rolling on tiny plastic beads in a container such as the tray of a ripple tank.

A stroboscopic photograph of a collision will show the distances travelled in equal time-intervals and the directions for the pucks before and after a collision.

Set up a camera directly above the collision plane as shown in Figure 10.13.

Take photographs of several collisions with the objects moving initially at various speeds and in various directions (or use the stroboscopic photographs provided on pages 116 and 117).

Calculate the momentum values as you did in the one-dimensional cases. Also, measure and record the direction of each momentum vector. To do this, first choose a reference direction, say, the initial direction of object A. Mark this reference axis on the photograph. Measure the angle clockwise (+), or counter-clockwise (−), to each of the other vector directions as shown in Figure 10.14a. Then draw a vector diagram to scale as shown in Figure 10.14b. Add the momentum vectors graphically on the diagram.

Q1 Was momentum conserved? (Compare both the magnitude and direction of $\vec{P}_{total}$ and $\vec{P}'_{total}$.)

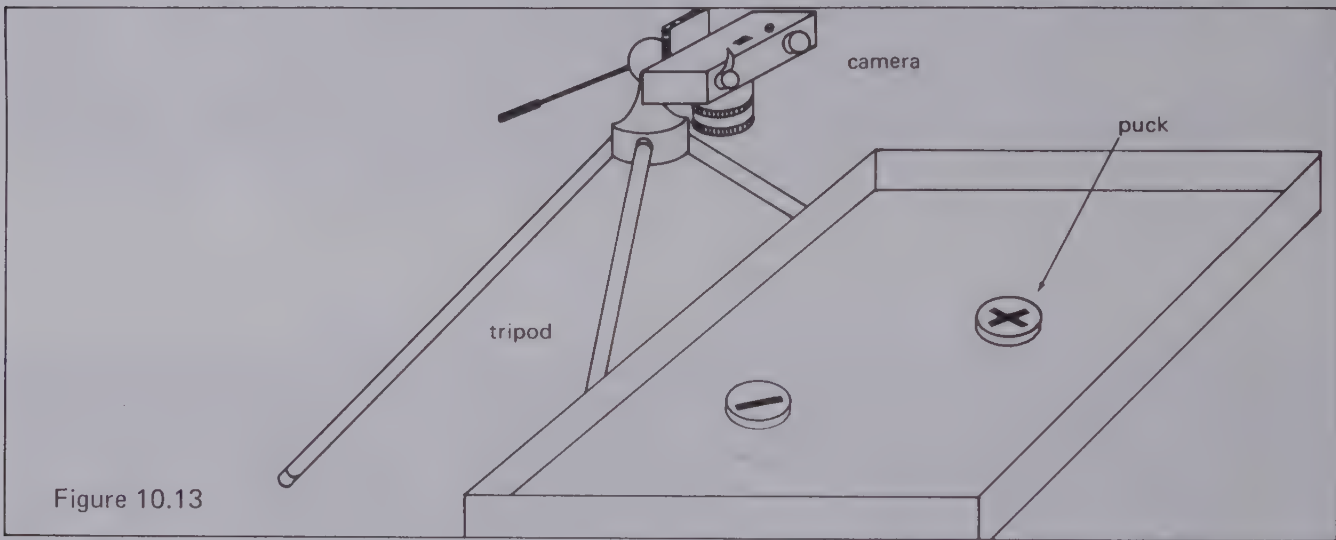


Figure 10.13

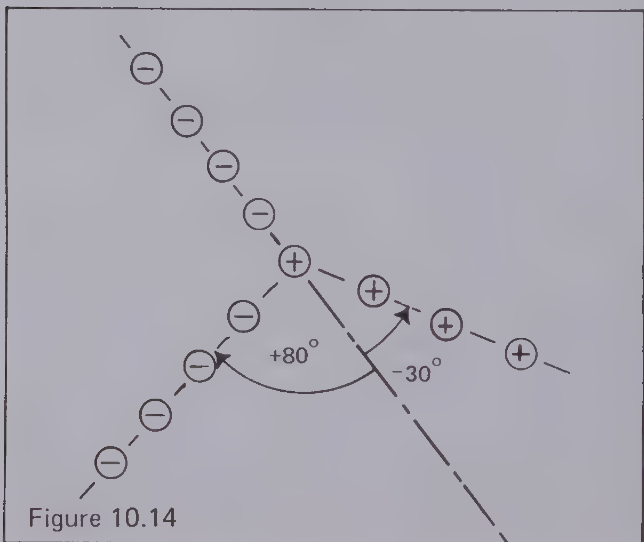
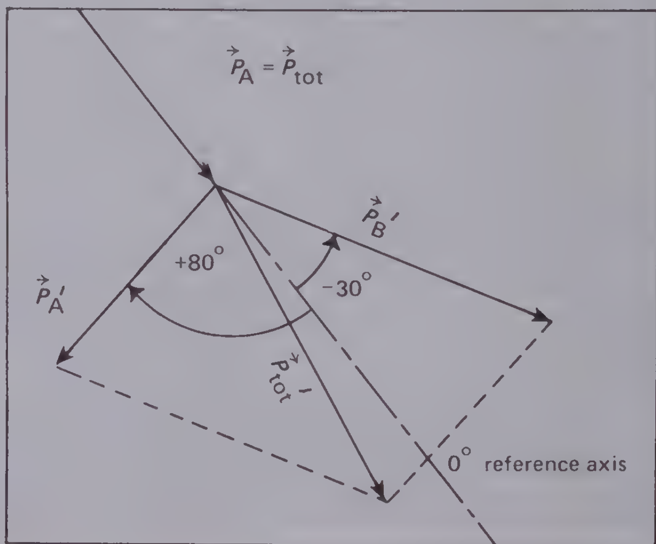


Figure 10.14



Additional Questions

EXPLOSIONS

In an earlier experiment (Experiment 5.3 in Unit 1) you studied an explosion between two objects.

Q2 Based on the results in that experiment, was momentum conserved for the explosion? Show calculations.

Q3 How do the forces acting on *A* and *B* compare in either a collision or an explosion?

ELASTIC AND INELASTIC COLLISIONS

As discussed earlier in Experiment 10.2 the quantity *vis viva* is also important in collisions.

Q4 In terms of *vis viva* $m(\vec{v})^2$, what is the distinction between an elastic and in a inelastic collision?

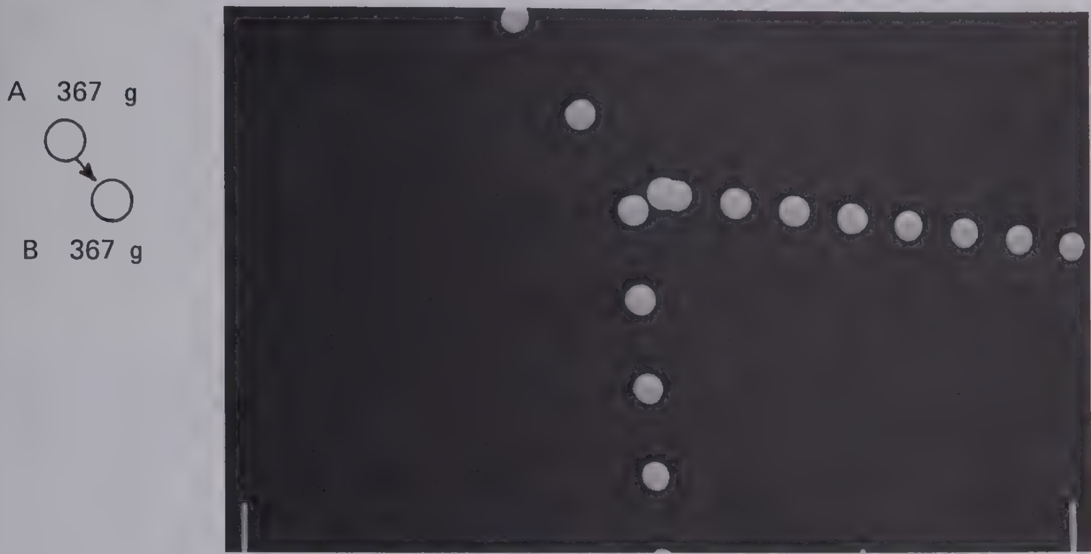


Figure 10.15 20 flashes per second

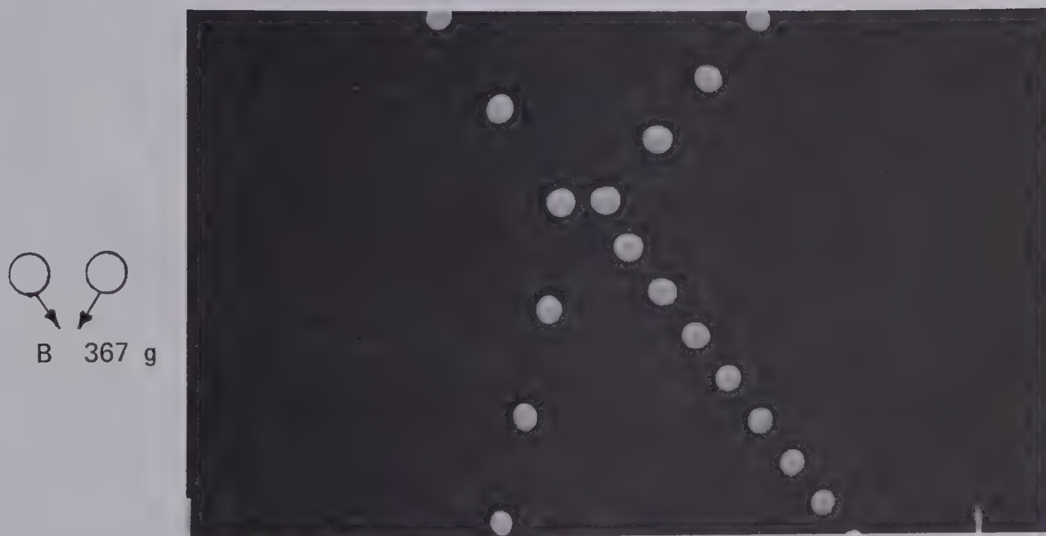


Figure 10.16 20 flashes per second

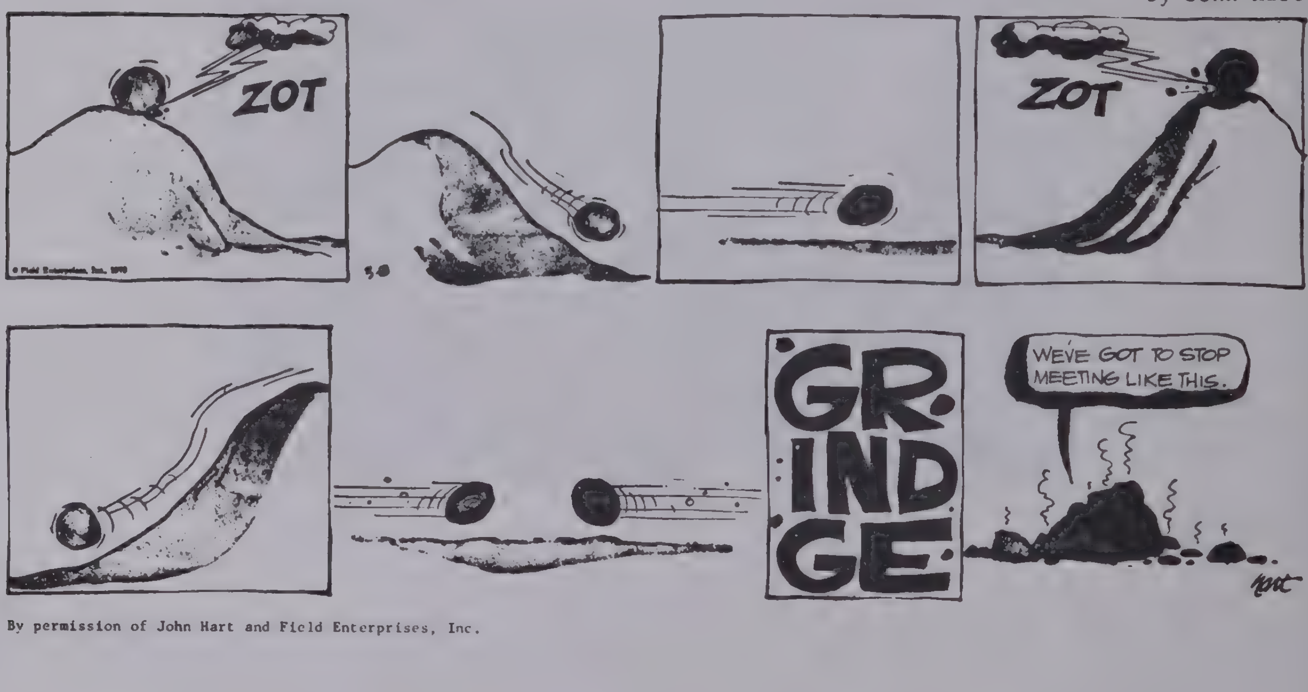
Figure 10.17 20 flashes per second

Activities

The energies flow from one body to another in such a way that an impressed force is transmitted to the projected body.

Johannes Philoponus (c. AD 517)

B.C. by John Hart



By permission of John Hart and Field Enterprises, Inc.

Activity 10.1 Conservation of Mass

There are several ways to illustrate the law of conservation of mass. Some of these are suggested below.

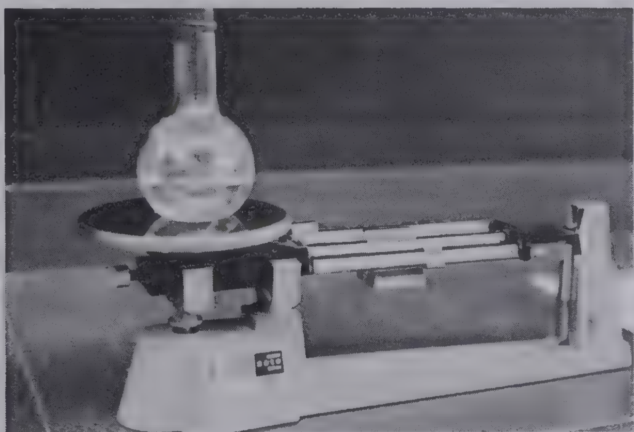
MIXING CHEMICALS

Obtain a micro test tube, 5g lead nitrate, 3g potassium iodide, a 250-ml flask with stopper, and an accurate balance.

Dissolve the lead nitrate in 100 ml of water in the flask, and the potassium iodide in 10 ml of water in the test tube. Lower the test tube carefully into the flask as shown in the photo below and place the flask on the balance. Adjust the balancing weights until the balance is in equilibrium.

Invert the flask so that the solutions mix. Describe any changes which occur. Is mass conserved?

Figure 10.18



FLASH BULB

On a very sensitive balance find the mass of a new flash bulb. Average several values.

Leave the bulb on the balance and flash it by attaching a battery. Try not to touch the bulb with your fingers. You do not want to change its mass by leaving fingerprints behind.

Describe changes which occur. Is mass conserved?

If the bulb filament burned in the air without the bulb's containing envelope, would its mass remain the same? Discuss.

MELTING ICE

Place an ice cube in a glass of water on a balance. Adjust the balance to equilibrium. Allow the ice to melt. What changes occur in the water and ice mixture? Is mass conserved?

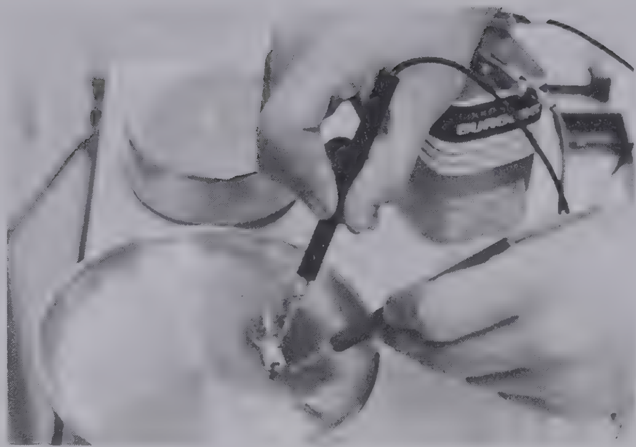


Figure 10.19

Activity 10.2 Momentum Exchange

Momentum conservation is expected in all situations. Study the situations below and see if momentum is conserved in each case.

RECOIL OF A DYNAMICS CART

Place a spring-loaded, dynamics cart on a smooth, level surface. Fire the spring by hitting the launching pin vertically so as not to give a horizontal push to the cart. Carefully describe the motions of the cart and spring. If the effect is too small to be seen easily, try reducing friction or use a heavier spring.

Q1 Is momentum conserved for the system of the cart and spring?

Q2 Why does the cart and spring system come to rest after a short while?

ACTION-REACTION TOY

Reconsider the action-reaction toy used in Demonstration 6 of the Introduction to Unit 1. Using the law of conservation of momentum, explain its behaviour.

BRICK AND CART

Begin with a dynamics cart on a smooth, level surface and a brick, hung on a string from a stand. Prepare to measure its velocity before and after it passes the brick with ticker tape and a vibrating timer or with a stop watch.

Launch the cart to pass under the brick. Just before the cart is directly below the brick, release the brick so that it falls on the cart. You will need to practise your timing for this.

Figure 10.20

Figure 10.21

Q1 What effect does the brick's vertical momentum have on the horizontal momentum of the cart?

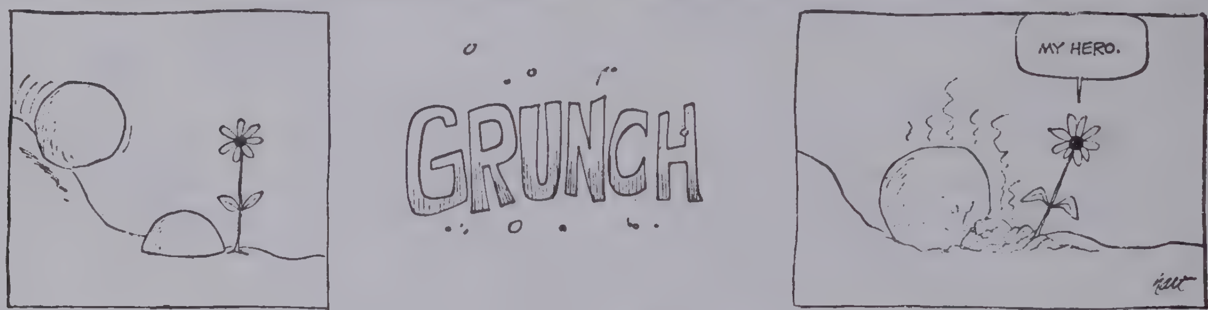
Repeat the experiment making necessary measurements and calculations to show that the total horizontal momentum of the cart-brick system is conserved.

Q2 What happens to the brick's vertical momentum?

Q3 What would happen if the brick were initially suspended from the cart and then were dropped off mid-way through its run? Try it.

Activity 10.3

Discuss the collision in the cartoon below by considering the laws of momentum and energy conservation.



Film Loop Notes

Film Loop 10.1 One-Dimension Collisions 1

This film loop shows two examples of head-on collisions between two steel balls, one initially at rest. Each ball is suspended from two wires so that it moves in a large, nearly-flat arc. Near the middle of their swings, where they collide, the balls are moving in an almost-straight line.

Project the film on a large piece of paper or a chalkboard. On this screen, mark positions, and measure distances and times, from which you can calculate the momenta of the balls before and after each collision.

First, watch the film without making measurements.

Devise your own method of accurately measuring distance and time. Choose a segment of arc near the collision point where the arc of each swing is almost a straight line and the ball's velocity is closest to being constant. Repeat your measurements several times and find an average for improved accuracy.

Calculate the velocity and momentum for each ball. (Use a positive or a negative sign to indicate the directions of these vector quantities.)

Estimate the uncertainty in each measurement and use it to find the uncertainty in the momentum of each ball.

Calculate the total momentum of balls *A* and *B* before and after the collision. Is momentum conserved within the limits of experimental uncertainty?

Keep your data and when you have studied energy in the next chapter, calculate the kinetic energies of the balls and compare to see if energy is conserved in each collision.

Film Loop 10.2 One-Dimensional Collisions 2

This film loop shows two other examples of one-dimensional collisions between two balls set up as in Film Loop 10.1.

Use the same methods as you did in Film Loop 10.1 to investigate conservation of momentum, and kinetic energy for each impact.

Film Loop 10.3 Inelastic One-Dimensional Collisions

In this film loop, the steel balls are covered with plasticine and supported as in Film Loop 10.1. On impact the balls stick together. This is an inelastic collision.

Use the same methods as you did in Film Loops 10.1 and 10.2 to investigate conservation of momentum for inelastic collisions.

Is there any difference between elastic and inelastic collisions with respect to conservation of momentum?

Keep your data and after studying energy, calculate the kinetic energies and compare the total energy before and after each impact. How do elastic and inelastic collisions compare with respect to energy conservation?

Film Loop 10.4 Two-Dimensional Collisions 1

In this film loop, you will see collisions between two balls suspended from single wires so that they can glance off each other and move in different directions. The camera is placed as shown so that it records only the horizontal components of the balls' motions. Although each ball swings in a large arc, this path is almost in the horizontal plane near the point of impact.

Project the film loop on a large piece of paper or chalkboard. First determine the directions of the balls' motions before and after the collision. Draw the "best", straight line through several points along each path. Then, to determine the magnitude of the velocity of the balls before and after their impact, use the same method as you did for the one-dimensional collisions in Film Loops 10.1, 10.2, and 10.3.

Calculate the momentum of each ball and add them vectorially to obtain the total momentum for both balls before and after the collision.

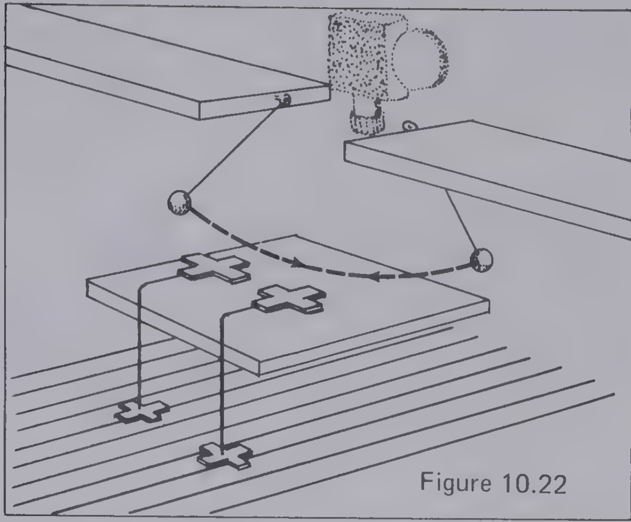


Figure 10.22

Is momentum conserved?

Keep your data and after studying energy, calculate the kinetic energies. Then compare the total energy before and after collisions.

Film Loop 10.5 Recoil

The first scene shows a cannon fired at the fort on Isle Ste. Hélène near Montreal. In subsequent scenes a small brass laboratory cannon simulates the firing and recoil of the big gun. The mass of the miniature cannon is 350 g. The projectile's mass is 3.50 g. The firing is shown in slow motion.

Q1 Why is there a delay between the time when the fuse is lit and the time when the bullet leaves the cannon?

Project the film on a large piece of paper or a chalkboard. By timing the projectile over a fairly large displacement, determine its velocity. (Use apparent values. It is not necessary to take the scale or slow motion factor into account in your analysis.)

Assuming momentum is conserved in the explosion, what is your prediction for the cannon's recoil velocity? Calculate a value. Then run the film again and this time make measurements from which you can determine the cannon's velocity. Find the percentage error between your prediction and measurement.

Q2 What are sources of error in these values?

Keep your data, so that when you have studied kinetic energy in the next chapter, you may consider the firing from an energy point of view.


Figure 10.23

Chapter 11. Energy

In our industrialized society, energy is put to practical use by devices such as electric motors. The rate at which this energy is supplied and converted to useful work by such devices is an important engineering problem.

Experiment 11.1 Power of a Motor

In this experiment you will investigate the energy output (work done) and the rate at which energy is used (output power) by a small electric motor lifting a load vertically.

Set up the apparatus as shown in Figure 11.1.

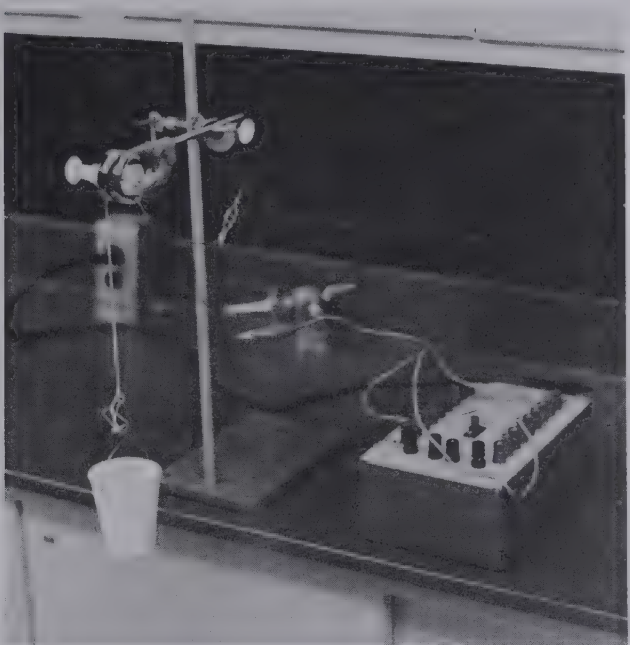


Figure 11.1

With a small load of sand in the bucket, start the motor. If the motor will not raise the load, turn the motor off immediately, and reduce the load. If it accelerates the load, turn the motor off, return the load to your starting point, and increase the load.

Adjust the load until the motor will raise it at a slow, uniform speed.

Measure the time required for the motor to lift the load through 1 metre at a slow, uniform rate. Repeat three or four times and average the values. Record the average.

Record the mass of the load including the mass of the bucket.

Analysis

Calculate the work done in raising the load 1 metre. (This work is done against gravity so that the work done on the load equals the gain in the object's gravitational potential energy.)

$$W_{output} = ma_g d.$$

Calculate the power output of the motor in lifting the load.

$$P = \frac{W_{output}}{T}.$$

Q1 Is the entire energy output of the motor used to lift the weight? Discuss.
Q2 Why was it necessary to adjust the load until the motor would raise it at a constant speed?
Q3 What is the motor's power in horsepower?

Experiment 11.2 Energy of a Moving Object

When an unbalanced force is applied to an object, causing its speed to change, work is done on the object. In other words, energy is transferred to the object if it accelerates, or, the object loses energy if it decelerates. In this experiment, you will apply a force to a dynamics cart initially at rest and attempt to discover how the gain in the kinetic energy of the cart (this energy due to motion is often represented by *K.E.*) is related to its speed, *v*, and mass, *m*.

There are two ways in which the force can be applied. You may choose to do the experiment using either a spring scale to pull the cart or a rubber band to launch it.

One other option which you may have is using a glider on an air track instead of the dynamics cart. The procedure would be the same.

Procedure A Spring Scale

Set up the dynamics cart on a smooth surface, in order to reduce friction as much as possible. You will also need a spring scale (calibrated in newtons if possible), a stopwatch, and a metre stick.

First practise pulling the cart with a constant force, say 1 newton (1 N $\simeq$ 100g force).

Figure 11.2

K.E. AND SPEED (CONSTANT MASS)

To determine the speed of the cart at the finish, you need to measure only the time T for the front of the cart to move from rest at the start, to the finish. The final speed v can be found from the definition, assuming constant acceleration,

$$v = 2 \times v_{average},$$

or $$v = 2 \times \frac{distance}{T}.$$

Mark off a convenient distance (two metres or as long as possible if less than two metres) on the table. When everything is ready, do your first run with a force of 1.0 N. Repeat with forces of 0.5 N and 2.0 N.

Calculate the cart's speed and tabulate the values for each case.

Measure and tabulate T in each case. Try other force-values if you have sufficient time.

Calculate the work done on the cart in each case and tabulate your results.

Q1 Assuming friction forces are very small, how is the work done related to the *K.E.* gained by the cart in each case?

Plot a graph of the cart's speed (v), versus the gain in *K.E.* then of speed squares (v^2), versus *K.E.*

Q2 Based on your results, what is the relation between the *K.E.* of a cart of constant mass and its speed? (Write a variation statement.)

K.E. AND MASS (CONSTANT SPEED)

To find how the *K.E.* of the cart depends on its mass is more difficult to determine with this apparatus, but if you have sufficient time and patience, try it.

Begin with an unloaded cart. Pull it with a constant 1.0 N force over the measured distance and determine its speed for the run. Then double the applied force to 2.0 N and add masses to the cart until the cart reaches the same speed as before. Repeat with applied forces of 3.0 N and 4.0 N and record the mass necessary to give you the same speed in each case.

As before, if friction forces are small, the work done will be approximately equal to the cart's gain in *K.E.*

Calculate and tabulate the work done on the cart in each case.

Plot a graph of the cart's mass versus its *K.E.* (work done).

Q3 Based on your results, what is the relation between the cart's *K.E.* and its total mass?

Q4 What is the major source of experimental error in this part of the experiment?

Q5 How do your results compare with the relation $K.E. = \frac{1}{2}mv^2$ shown in the text on page 12?

Procedure B Rubber Band Launcher*

As in Procedure A, set up the dynamics cart on a smooth table where friction effects are reduced as much as possible. At one end of the table build a launcher as shown in Figure 10.2, page 107. Devise a means of measuring the speed of the cart after its launch.

K.E. AND SPEED (CONSTANT MASS)

Fix one elastic band on the launcher, push the cart against the stretched band to a starting point marked on the table with masking tape and then launch the glider. Measure its speed (v) and adjust the starting point until your launch speed is a convenient value between 0.5 m/s and 1.0 m/s. Test other elastic bands singly until you find four which will each launch the cart with approximately the same speed. Be sure to always use the same starting point.

Now, measure the launch speed of the cart when launched with two, three, and then four bands. Tabulate your results.

*This experiment is similar to one in an excellent book, *Physics is Fun* by J. Jardine (published by Heinemann Educational Books Ltd., London)

Q1 How are the work done by the launcher and the *K.E.* of the cart related to the number of rubber bands in the launcher?
Q2 Why is it important to always launch from the same starting point?

Plot a graph of the cart's speed (v) versus the number of bands. Also plot the cart's speed squared (v^2) versus the number of bands.

Q3 Based on your results, what is the relation between the *K.E.* of the cart of constant mass and its speed? (Write a variation statement.)

K.E. AND MASS (CONSTANT SPEED)

This part of the experiment is more difficult and requires a little time and patience. Try it. Begin with one band and the cart. Find its launch speed. Now add another band to the launcher, and add mass to the cart until its launch speed is the same as before. Repeat with three, then four bands in the launcher. Be sure to extend the bands by the same amount each time. Tabulate your data.

Q4 Based on your data, what is the relation between the cart's *K.E.* and its total mass if the speed is constant? (Write a variation statement.)
Q5 What is the major source of experimental error in this part of the experiment?
Q6 How do your results compare with the relation $K.E. = \frac{1}{2}mv^2$ shown in the text on page 12?

Experiment 11.3 Energy of a Falling Object

As an object falls, it loses gravitational potential energy. This energy is transformed to other types of energy. If air resistance is small, most of the potential energy will be transformed into kinetic energy as the object accelerates. In this experiment you will study the change in potential energy and kinetic energy for a falling object and see how these changes are related.

You can calculate the changes in potential energy and kinetic energy from measurements of the distances travelled vertically and the time-intervals for those distances. To do this, use a vibrating timer and ticker tape or take a stroboscopic photograph as outlined in the following procedures.

Procedure A Ticker Tape attached to a Falling Object

Setting up a vibrating timer approximately 2 metres above the floor as shown in Figure 11.3. Place the timer so that the tape passes through it vertically.

Thread approximately 2 metres of ticker tape through the timer and attach one end with masking tape to a heavy mass (0.5 kg will do nicely).

Measure the initial height of the mass.

Hold the ticker tape vertically with the mass just below the timer, start the timer, and then release the tape.

After the run, calibrate the timer to determine time-intervals in seconds.

Note the mass of the object and its initial height

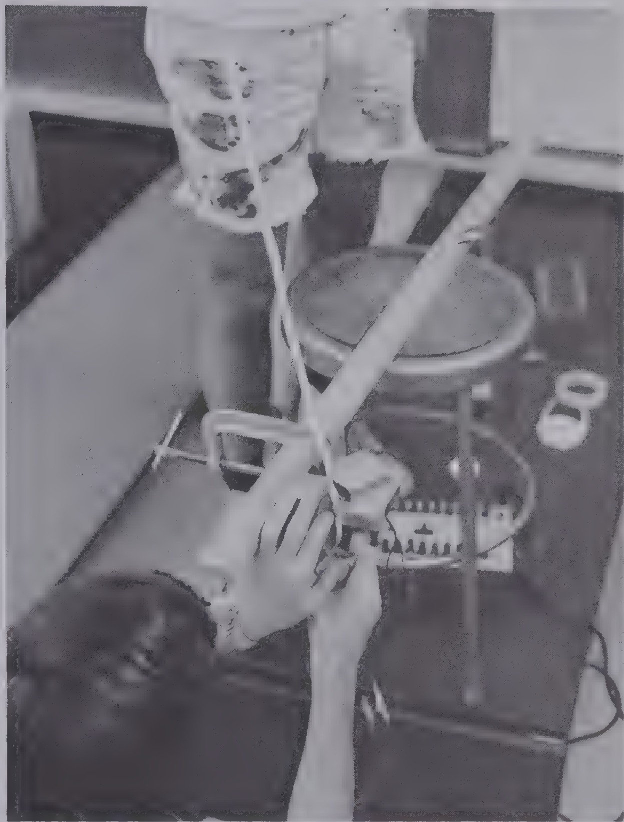


Figure 11.3

Procedure B Strobe Photograph of a Falling Sphere

Take a photograph of a sphere falling in front of a dark background in a darkened room. Be sure to include a reference metre stick in the picture so that you can calculate actual distances based on measurements from the photograph.

Measure the initial height of the ball.

Note the period of the stroboscope and the mass of the sphere.

Analysis

Divide the object's path into a convenient number of equal time-intervals (equal number of dots or flashes) starting from the initial point. Label the beginning of each interval *A*, *B*, . . . on the tape or photograph as shown in Figure 11.4.

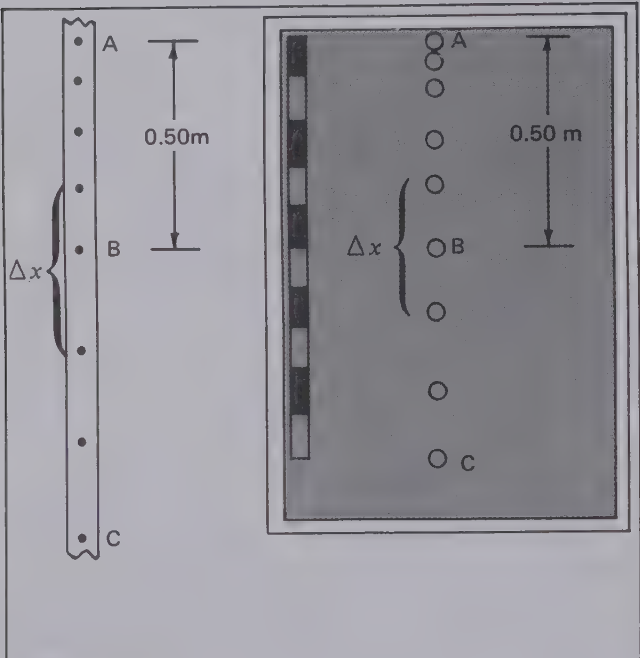


Figure 11.4

Measure the distance travelled from the initial point to the end of each interval and tabulate data as shown in Table 11.1. Calculate the object's height above the floor at each point by subtracting the distance fallen from the initial height.

To find the object's speed at a point such as *B*, measure the distance Δx between the dots or images immediately before and after the location of *B*, as shown in Figure 11.4. Then determine the time elapsed Δt, as the object moves through Δx. From these and similar measurements, calculate the speeds of the object at each point chosen and tabulate results. (Note: $v_{instantaneous}$ at $B = v_{average}$ for a small interval centred in time at *B*.)

Calculate for the object at each point (a) gravitational potential energy (*P.E.*), (b) kinetic energy (*K.E.*), and (c) total energy (*K.E.* + *P.E.*).

Plot a graph of *P.E.* versus *h* and then on the same axes, graph *K.E.* versus *h* and total *E* versus *h*.

Q1 How does the change in *K.E.* at any point during the fall compare with the change in *P.E.*?

Q2 How does the total energy *E* behave during the fall? How can you account for this?

Q3 Within the limits of experimental uncertainty, is the falling object a conservative system? Discuss using your data.

Q4 If you throw a ball vertically from the floor, how would quantities such as *K.E.*, *P.E.*, and total *E* behave? Discuss.

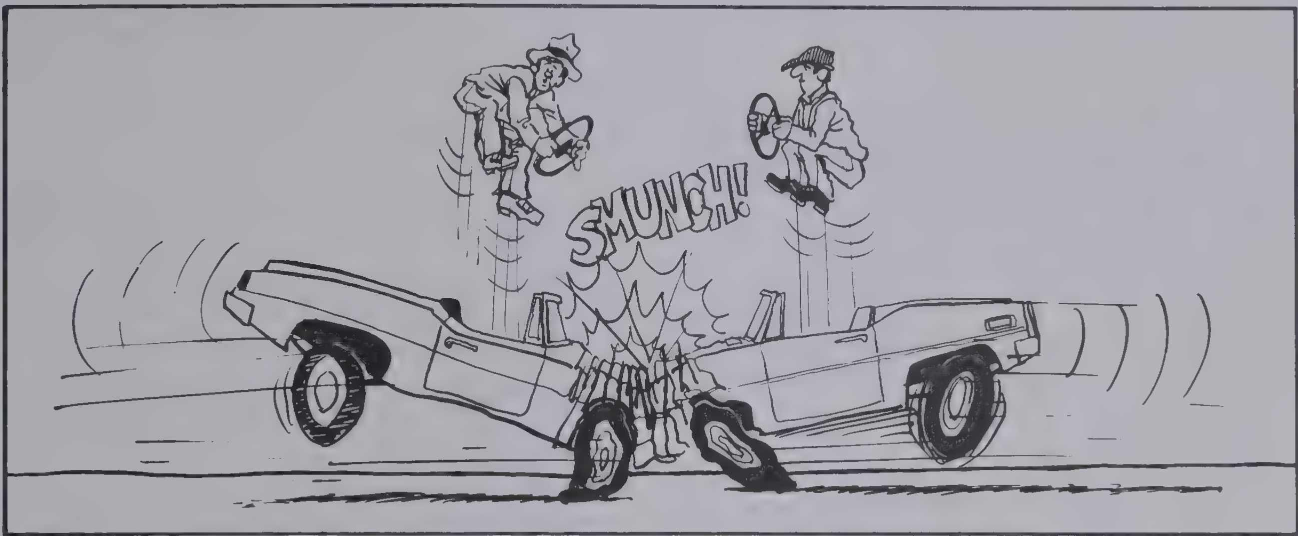
Table 11.1

	Distance from the beginning (m)	Height from floor (m)	Speed (m/s)	P.E. ( )	K.E. ( )	Total E = (P.E. + K.E.)
A						
B						
C						
D						
•						
•						

Activities

Physical concepts are free creations of the human mind, and are not, however they seem, uniquely determined by the external world.

A. Einstein (1879-1955)
L. Infield (1898-1968)



Activity 11.1 Energy Transformations

Below are several interesting devices in which energy transformations occur. Most of them will be available in your laboratory. Study some or all of them and in each case identify the types of energy and note the energy transformations involved. For example, consider a cart launched along a desk by a rubber band. The energy transformations could be shown in the following way.

Elastic Potential Energy (band) → K.E. (cart) → Sound (air)
K.E. (cart) → Heat (desk and wheels)

RADIOMETER

Shine a light bulb on the radiometer and note the direction in which the vanes spin (black or shiny side trailing).

Is it heat energy or light energy from the bulb which powers the radiometer? Devise a test or argument to determine which it is. Then outline all energy transformations involved.

THERMOCOUPLE

Place the junction of a thermocouple connected to a microammeter or sensitive galvanometer in a Bunsen burner flame. Note what happens and identify energy transformations.

PHOTOCELL

Shine a light source on a photocell connected to an ammeter or a small electric motor and identify the energy transformations.

BATTERY AND BULB

Connect a bulb to a dry cell and note the energy transformations.

PAPER CLIP

Hold one round end of a paper clip to your lips. Then straighten it quickly and hold it to your lips again. What happens?

ACID AND WATER

Carefully add some concentrated sulphuric acid to a beaker one-quarter full of cold water. Is there any change? ALWAYS ADD ACID TO WATER. DO NOT TOUCH THE SOLUTION TO DETECT A CHANGE. DO NOT SPILL THE SOLUTION OR THE ACID.

HAND GENERATOR

Turn a hand generator connected to a bulb. While still turning disconnect or remove the bulb. Account for what happens.

MICROPHONE AND SPEAKER

Connect a microphone through an amplifier to a speaker. What energy transformations occur when you speak into the microphone?

AUTOMOBILE THERMOSTAT

Place an automobile thermostat in some cold water. Heat the water to the boiling point and then allow it to cool. Watch the thermostat and note the energy transformations.

GEIGER COUNTER

Turn the counter on and put a radioactive sample near the tube and list the energy transformations. List all of the types of energy that you can think of. Suggest other devices and transformations which were not set out in the activity.

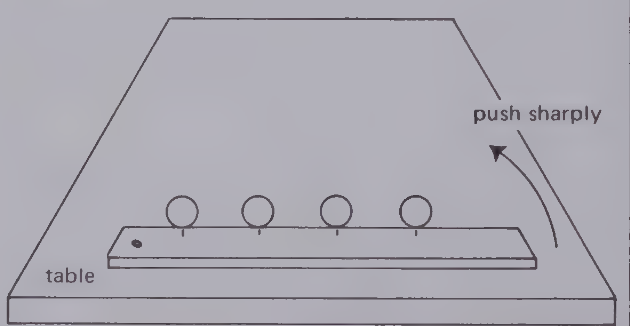
Activity 11.2 Student Power

Measure your power walking or running up a flight of stairs. To do this you will need to know the height of the stairs in m, your mass in kg and the time taken to go up the stairs in seconds. Try to include several people in this activity. Perhaps a schoolwide contest could be organized.

Activity 11.3 Launching Pennies

Space four pennies at equal intervals against a metre stick pivoted at one end on a smooth, level surface. Launch the pennies simultaneously by pushing the free end of the ruler sharply.

Figure 11.5



Q1 How should the initial velocities of the pennies compare? Why? (Consider distance travelled by each during launch and the time-interval for each coin.)

Q2 How does the initial *K.E.* of each of the coins compare? Why? Making assumptions about the friction forces which slows each coin down, explain your observations.

Q3 For each coin, what is the relationship between the initial velocities and the distances travelled after launching?

Activity 11.4 What's in a Spring?

Place the spring end of a dynamics cart against a wall or solid bumper.

Hit the launching pin and measure the launch speed of the cart. Calculate the *K.E.* of the cart and determine the *P.E.* initially stored in the spring.

Double, then triple the mass launched and repeat the experiment. Do your results confirm the equation $K.E. = \frac{1}{2}mv^2$?

Predict how high the compressed spring would launch a steel sphere vertically. Try it to test your prediction.

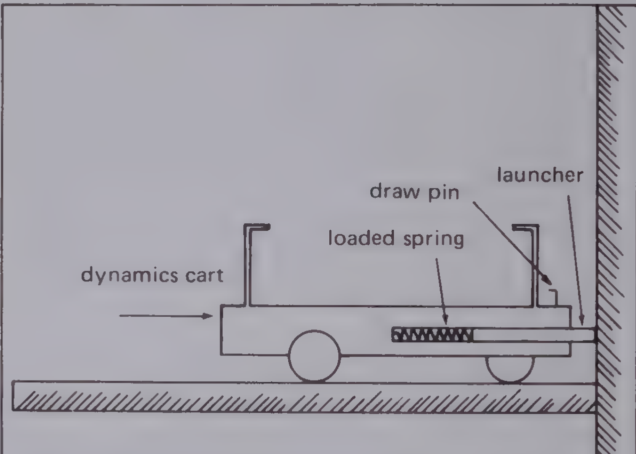


Figure 11.6

Acitivity 11.5 Energy of a Pendulum

As a pendulum swings there is a continuous exchange between *K.E.* and gravitational *P.E.* On the downswing *P.E.* becomes *K.E.* If energy is conserved and there are no losses, then the loss in *P.E.* should equal the gain in K.E. between the starting point and lowest point in the swing. You can check this by analysing a pendulum's motion.

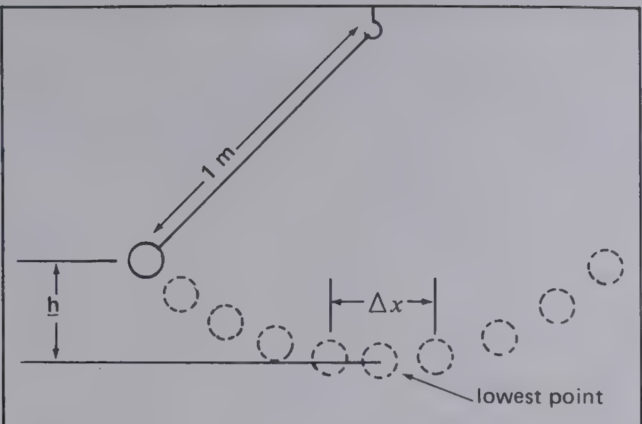


Figure 11.7

To obtain data, photograph a simple pendulum consisting of bob (a 0.5 kg sphere works well) suspended by a string approximately 1 m long. For the photograph use: (a) an electronic stroboscope, (b) a blinky bulb attached to the bob, or (c) a bulb powered ay an AA cell taped to the bob and photographed through a disc stroboscope. Photograph one-half cycle of the pendulum. Open the shutter just before releasing the bob about 10 cm above the swing's lowest point and close it just as the bob reaches peak height at the other side of the swing.

Choose a small distance interval Δx with its centre at the low point of the swing and calculate the instantaneous velocity $\vec{v}$ there, by dividing Δx by the time elapsed. Calculate the *K.E.* of the bob at the bottom of the swing.

Measure the vertical height h, of the starting point above the low point of the swing. Calculate the loss in *P.E.* of the bob as it moves from the start to the lowest point. In the same way calculate the gain in *P.E.* during the second half of the swing.

Q1 Is energy conserved between
(a) the starting point and the lowest point ?
(b) the lowest point and the finish point?
Show calculations to justify your answers.

You can find the *P.E.* and *K.E.* of the bob at any point along the swing in a similar way. Plot graphs on the same axes, showing (a) *P.E.* versus time, (b) *K.E.* versus time, and (c) (*P.E.* + *K.E.*) versus time.

Q2 Is energy conserved during the entire swing? Discuss using your graph.
Q3 Using the data, can you estimate how long the pendulum should continue to swing? Try it.

Activity 11.6 A Law You Can Trust

How strong is your faith in the law of conservation of energy? Stand against a solid wall and against your nose, hold a heavy pendulum bob such as an inertia ball or a shot suspended from the ceiling.

Let the pendulum swing and wait in the same spot until the pendulum swings back. CAUTION: DO NOT PUSH THE PENDULUM.


Figure 11.8

Film Loop Notes

Film Loop 11.1 Conservation of Energy—the Pole Vault

In this loop, you can take a look in detail at a pole vault. The situations are presented so that you can make actual measurements from the loop in order to study conservation of energy.

In the first sequence, you see the vault at normal speed. Then it is repeated in slow motion. List the energy transformations which take place from the moment the vaulter starts running toward the bar until he lands.

Next, you should analyse the energy of the system (including vaulter and pole) by making measurements in three situations. It may help you to know that the pole vaulter is 1.83 m tall and has a mass of 68 kg. The bar which he clears by about 0.3 m, is set at 3.5 m.

Situation 1. The runner's position is "stopped" at 1/250-s intervals in front of two markers 1.00 m apart. Use these stopped frames to find his speed and kinetic energy (*K.E.*) as he is running.

Situation 2. At this point, on his way up, the vaulter's centre of gravity is 1.02 m above his heels. Once again, use the "stopped" frame sequence to find his speed and *K.E.* Also calculate his gravitational potential energy (*P.E.*) relative to the ground at this point.

Part of the energy of the system is stored as elastic potential energy in the deformation of the pole. In the loop's final sequence, a measurable force is applied by a windlass to bend the pole to its approximate shape in this situation. Energy stored or work done in bending the pole equals (average force) x (distance through which the force acts). Find the average force in newtons by averaging the initial and final forces applied by the windlass.

From a closeup, you can see the distance through which the force acts during a single pull. Count the number of times the crank handle is pulled and calculate the total distance. Finally, compute the elastic *P.E.* stored in the pole.

Using your values of *K.E.*, gravitational *P.E.*, and elastic *P.E.*, what is the total energy of the system at this point? How does this total compare with his initial *K.E.*? Can you account for any difference?

Situation 3. Determine his gravitational *P.E.* at this point, where the vaulter is moving very slowly as he clears the bar. Not all of this energy comes from the initial *K.E.* You will notice that in order to get over the bar the vaulter does work on himself with his arm muscles. This additional energy input is difficult to measure but watch the loop carefully between situations 2 and 3 and estimate the distance in m through which he lifts his mass with his arms. Calculate the work done by his arm muscles.

How does the vaulter's gravitational *P.E.* at the top compare with the sum of his initial *K.E.* and his muscular energy? The agreement of your results will depend on your approximations and on other factors which have been neglected as well as on the uncertainty of your measurements (10% agreement is reasonable). What other forms of energy in the system have been neglected at the top? Why? What other sources of error are there?

Figure 11.9

Chapter 12. The Energy Crisis

From ancient times, man has used machines to extend his capacity to work. He probably learned most about these machines through experience and you can do the same in the experiments in this chapter.

Experiment 12.1 Levers

Levers have been used for centuries as simple machines which gain a mechanical advantage for the user. There are three classes of levers defined by the arrangement of three points along the lever: the load, the force applied (effort), and the fulcrum. In this experiment you will investigate the law of the lever and measure the mechanical advantage and efficiency of levers in each of the three classes.

FIRST-CLASS LEVERS

Set up a first-class lever as shown in Figure 12.1 or 12.2.

Figure 12.1

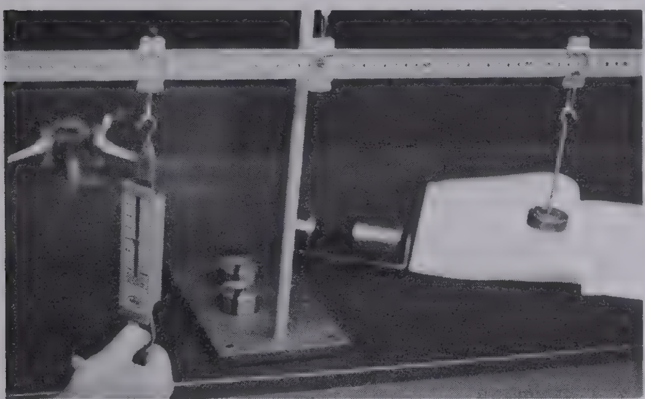


Figure 12.2

To measure the effort use a weight-hanger and weights or a spring scale calibrated in newtons.

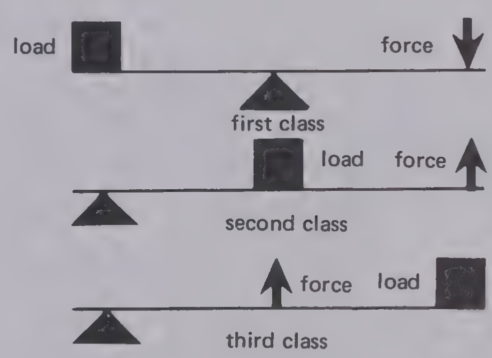
To begin, place the fulcrum at the mid-point of the metre stick. Locate a load of 200 g, 25 cm to the left of the fulcrum. (Load arm, LA = 25 cm.) Find the effort acting at 50 cm, (Force arm, FA = 50 cm) which will keep the lever in equilibrium. Repeat the experiment for various loads located at different positions, and measure the effort required to balance the lever when the force is applied at various distances from the fulcrum. If you measure the force with weights hung on a weight-hanger, then you can measure both the force and load in grams. If you measure the effort with a spring scale calibrated in newtons, then calculate the gravitational force acting on the load in newtons also. Tabulate results in a table with headings similar to Table 12.1.

Table 12.1

Load L ( )	Load Arm LA ( )	Effort F ( )	Force Arm FA ( )

Q1 What simple relationship exists among the four quantities measured and tabulated in the first four columns of Table 12.1? Show calculations based on the data.

Figure 12.3



Calculate and tabulate the mechanical advantage of the lever in each case.

$$\text{Mechanical advantage} = \frac{\text{Load}}{\text{Effort}} .$$

Q2 Why is a first-class lever advantageous? List some situations in which one would be useful.

You have looked at the relation between the effort and the load when the lever is in equilibrium at rest. Now investigate the relationship between the input energy or work done by the effort, and the output energy or work done on the load, when it is moved. Set up the lever with a load of 200 g, 25 cm from the fulcrum as before. Apply a force at 50 cm from the fulcrum on the opposite side, in order to lift the load slowly and steadily a height of 5 cm. Measure the effort (F), and the distance (x), through which it acts in lifting the load.

Calculate the energy input ($F.x$), and energy output (gain in the load's gravitational PE). From this find the efficiency of the lever.

$$\text{Efficiency} = \frac{W_{output}}{W_{input}} \times 100\%.$$

Repeat for other situations and compare results.

Q3 Distinguish clearly between the meanings of mechanical advantage and efficiency.

Q4 If you have a mechanical advantage greater than one, does this mean the energy gained by the load is greater than the work done by the force? Discuss using your results.

Q5 Is energy conserved within the limits of experimental uncertainty for the lever? Discuss using your data.

Q6 Why is the lever not 100% efficient?

SECOND- AND THIRD-CLASS LEVERS

Experiment with the apparatus changed to the configuration of a second- or third-class lever.

Find the mechanical advantage and efficiency for each case.

Q7 State general rules about the mechanical advantage of all levers of (a) the second class and (b) the third class.

Experiment 12.2 Pulleys

In this experiment you can investigate the advantages of using a single pulley or a system of two or more pulleys.

Procedure A Single Pulley

Using a spring scale, compare the force (effort) required to lift an object such as a 0.5-kg mass, vertically first, using the spring scale alone and then using a single pulley in addition to the scale as shown in Figure 12.4 and in Figure 12.5.

You probably found that you gained a mechancial advantage with the pulley.

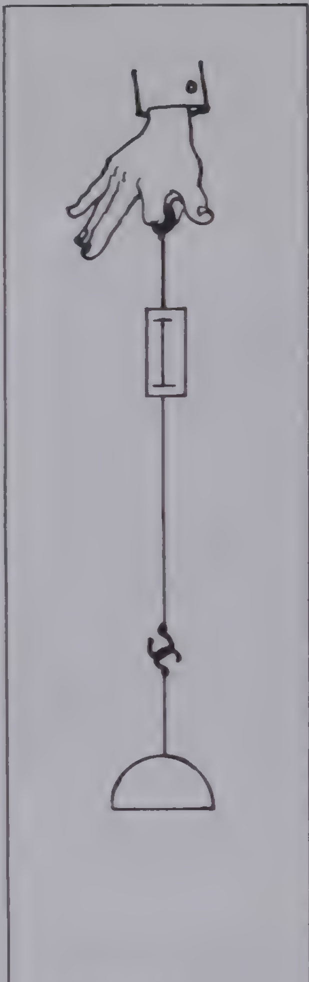


Figure 12.4

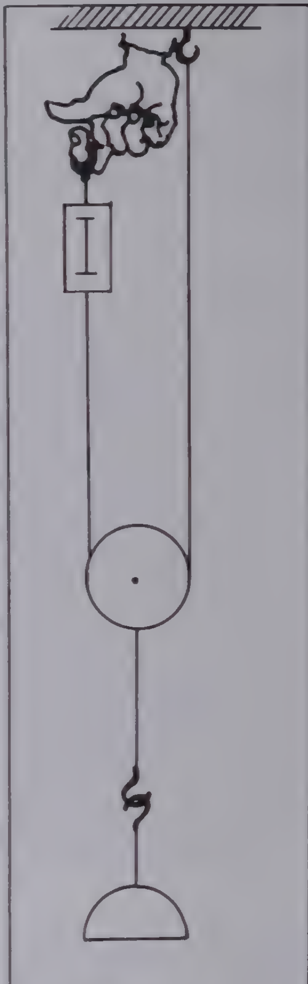


Figure 12.5

Q1 What is the mechanical advantage of the single pulley (a) ideally, (b) based on your data?

Q2 Did you get something for nothing? In other words, since you used less force with the pulley, did you do less work to lift the object than with the straight lift? Repeat the experiment and measure distances so that you can calculate the energy input and energy output.

Q3 What is the efficiency of this single pulley?

Q4 Was energy conserved in each lift? Discuss.

Q5 How would the results have been affected if you had pulled the spring scale at an angle as shown in Figure 12.6. Try it.

Figure 12.6

Procedure B Multiple Pulleys

Combine single or double pulleys in some arrangement such as the one shown in Figure 12.7. Use a 1-kg mass as the load, and measure the applied force required to lift it at a slow, constant speed. From the results, calculate the mechanical advantage and efficiency of each combination.

Q1 What happens to the mechancial advantage and efficiency as the number of pulleys is increased? Why?

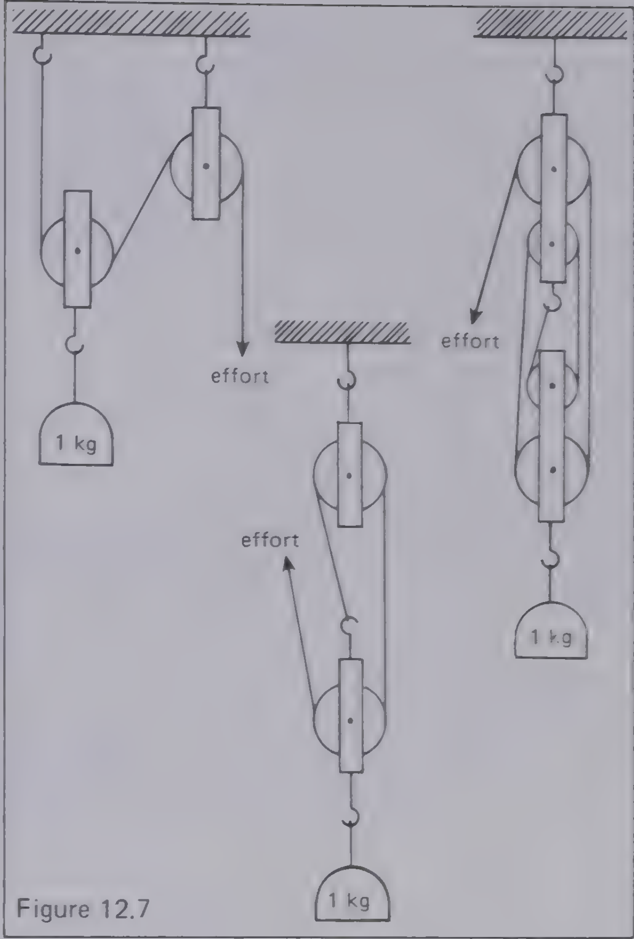
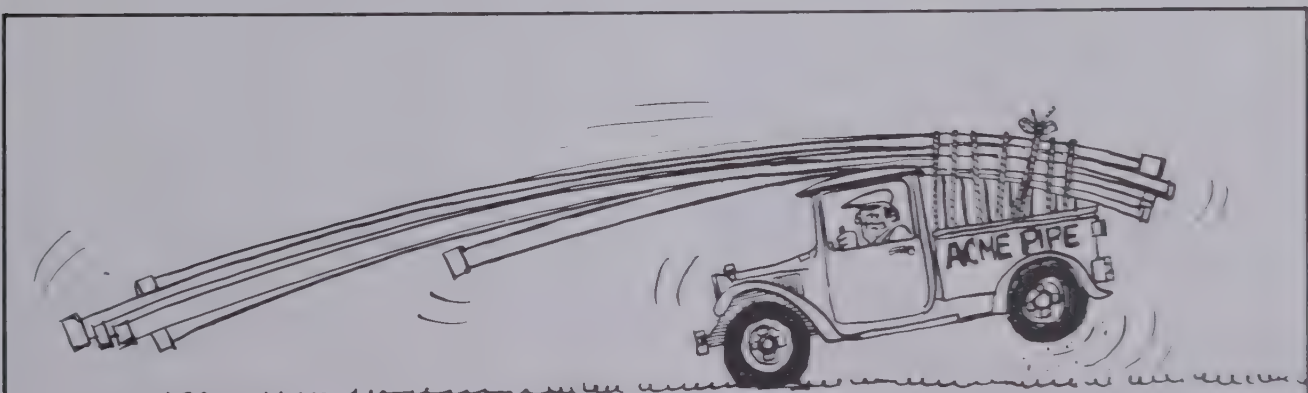


Figure 12.7

Activities

I do not say: science is useful because it allows us to construct machines; I do say: machines are useful, for by working for us they permit more time to study science.

Henri Poincare



Activity 12.1 Inclined Plane

What is the advantage of an inclined plane? Investigate this machine by measuring the work input and work output expended in pulling an object (such as a block of wood) up an incline using a spring balance or weight and pulley as shown.

Figure 12.8

Activity 12.2 The C-Clamp as a Machine

Obtain a *C*-clamp and study its characteristics as a machine. First you can determine its pitch simply by measuring the distance advanced by the clamp for a large number of turns (reciprocal of turns per cm). Then by placing a load of at least 1 or 2 kg on the *C*-clamp and by rotating the handle through one half-turn, you can measure the force required to raise the load. You will have to carefully pull the spring scale for measuring force so that the force arm remains constant as you turn the clamp. Also, always keep the direction of the applied force at right angles to the handle.

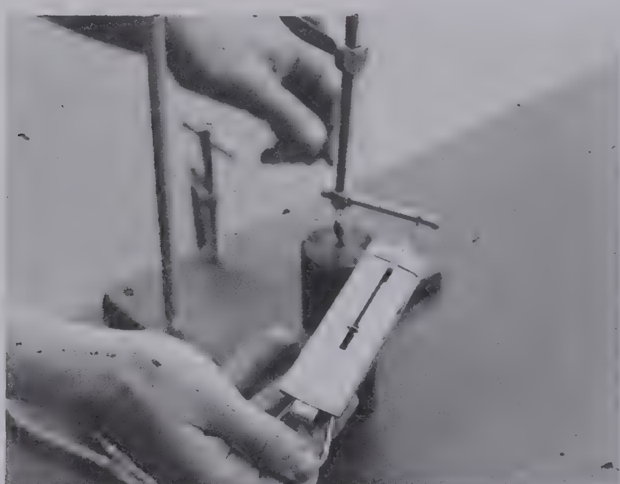


Figure 12.9

Calculate: (a) the mechanical advantage of the *C*-clamp, (b) the work input and output for the lift, and (c) the efficiency of the *C*-clamp.

Activity 12.3 Pulley Puzzle

Consider the pulley arrangements shown below and predict what should happen when effort is expended in the direction indicated. Then try each system. Comment on your results.

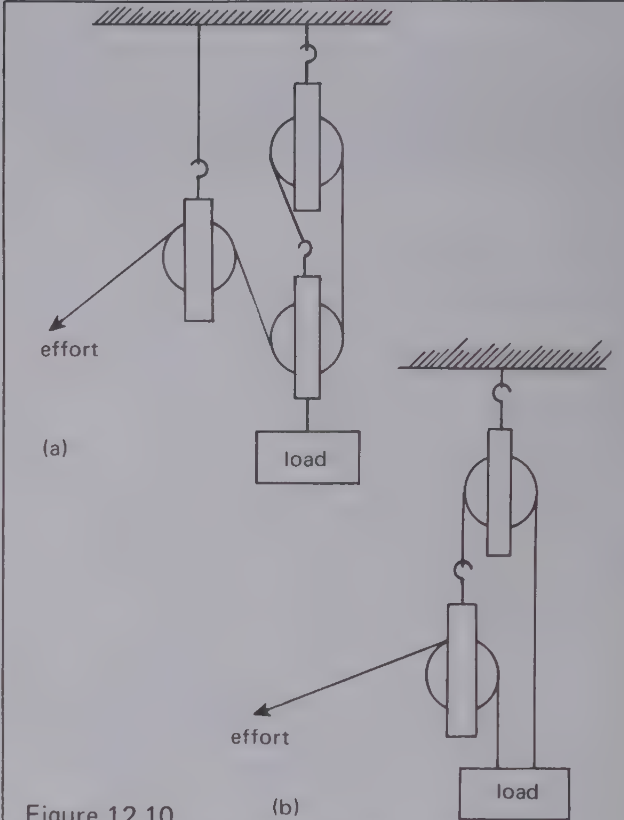


Figure 12.10

Activity 12.4 A Car Jack

An interesting and easily available machine is a car jack. With some ingenuity, you can determine its mechanical advantage and efficiency in jacking up a small car. To measure the effective load, you may consider the car as a second-class lever. The rear wheels are the fulcrum, the force is applied at the front of the car by the jack, and the car's weight between the jack and rear wheels is the load. To calculate the load you will need to find some data and to make some approximations for others.

Figure 12.11

Q1 What is the car's mass? You will find it given in pounds in the owner's manual. Convert to kg using the conversion factor 1 kg = 2.2 pounds.

Q2 What is the load? (What fraction of the car's mass will be lifted by the jack?) Notice that any overhang behind the rear wheels actually helps to lift the car. Estimate the effect of the trunk overhang.

Q3 Where does the load act? Even though the car's mass is distributed along the frame, for simplicity it can be considered to act at a point somewhere between the rear wheels and front bumper. Approximately where is this point?

Q4 What force on the front bumper would be necessary to lift off the ground (a) both front wheels, (b) one front wheel of your car?

Once you have estimated the force necessary to lift one front wheel off the ground, you can proceed to find the mechanical advantage of the jack. The force applied by the jack to the car's front bumper is the jack's load. You must measure the effort to apply this force. Devise your own method to measure the effort in newtons. Once this is measured, you can determine other quantities such as efficiency and mechanical advantage.

Q5 Estimate how much work you would do in jacking up one front wheel just high enough to change the tire.

Q6 Find out what power you can produce in jacking a car.

Activity 12.5 Energy and the Environment

Society's insatiable demand for, and sometimes profligate waste of energy has placed great strains on our environment. Another problem involving use of energy in automation is the displacement of men from jobs by machines.

Research some aspects of these problems in your community and look for ways in which science can help or is helping to solve them. One source of much information is the entire September 1970 issue of *Scientific American* which has been reprinted in the form of a book entitled *Energy and Power* available from W. H. Freeman and Company, San Francisco.

Chapter 13. Waves

The essentially new thing here is that for the first time we consider the motion of something which is not matter, but energy propagated through matter.
A. Einstein (1879-1955)
L. Infield (1898-1968)

In this chapter we shall investiage the behaviour of waves to see how they carry energy and to find out how waves interact with matter and with each other. The understanding we develop here will be useful in a great many topics of study in the remainder of the course.

Experiment 13.1 How Pulses Travel

Many waves travel too quickly or are too small to observe easily. In this experiment we shall look at waves in a long, "soft" spring where waves with large amplitudes move slowly.

To simplify matters, we shall look at *single pulses* rather than at wave trains which are just a series of pulses.

Figure 13.1

Obtain a long coil spring and, with your partner, stretch it out to a length of approximately 5 metres on a smooth, clean floor. Attach tabs of masking tape to the spring at 4 or 5 places along its length. To produce a *transverse* pulse, move your hand quickly from its rest position to one side and back at right angles to the axis of the stretched spring. Practise until you can send a pulse which travels down only one side of the spring.

Perform experiments to answer the following questions about the behaviour of transverse pulses. If you need additional equipment, ask your teacher.

Q1 Describe and compare the motions of the various points which you have marked along the spring, as a pulse passes by them.

Q2 Does the size or shape of a pulse change as it moves from one end of the spring to the other? If so, in what way?

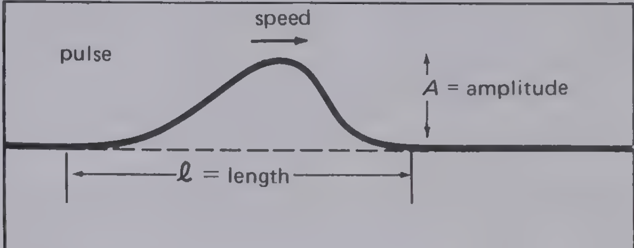


Figure 13.2

Q3 Does the speed of a pulse change as it moves along the spring? How do you decide?

Q4 What effect does changing (a) the amplitude A of the pulse, (b) the length ℓ of the pulse, have on the speed of the pulses?

Q5 Does a change in the tension of the spring have any effect on the speed of the pulse? If so, in what way?

Q6 Do similar pulses travel at the same speed in a different medium? Obtain a different spring (either heavier or lighter than the first one) and investigate this question.

There are other types of waves. To produce a *longitudinal* wave, hold your end of the spring with one hand, and compress several coils together with the other. Then release the compressed coils and look for wave motion in the spring. To produce a *torsional* wave, twist your end of the spring about its axis and watch the wave produced in the spring.

Q7 Do all three types of waves travel at the same speed in a given medium?

Additional Questions

Q8 When your hand shakes the spring, it does work on the spring by transferring energy to it. This energy travels along the spring in the form of a wave.

(a) If you produced two transverse pulses of the same length, but with amplitudes in the ratio 2:1, how would the amounts of energy transported by the pulses compare?
(b) What effect does the amount of energy in a pulse have on the speed of the pulse?
Q9 In an ideal medium, no energy of a pulse is lost as it moves along, but the spring used on a floor as in this experiment is not ideal.
(a) Why is it not ideal?
(b) Devise a method to find out how much of a pulse's initial energy is lost as it travels from one end of the spring to the other.

Experiment 13.2 Waves at a Boundary

In Experiment 13.1, we investigated behaviour of pulses as they moved along a continuous medium. What would happen if the medium were suddenly changed?

You probably noticed that when the pulses reached your partner's hand, holding the other end of the spring they did not stop or disappear.

Set up as you did in Experiment 13.1 and shake a transverse pulse on one side of the spring. (Call this side of the spring positive for convenience.) Repeat, and watch carefully the behaviour of the pulse, before, during, and after reflection from your partner's steady hand so that you can answer the following questions:

Q1 How do these characteristics of the incident and reflected pulses compare: (a) shape, (b) speed, (c) amplitude, and (d) sign (use the sign convention established at the beginning)?

Now fasten a second medium (a different coil spring or a piece of rubber tubing to one end of your spring). Stretch out both media until the tension in the first spring is approximately the same as it was before. In the first case start a transverse pulse at your end and watch what happens to the pulse as it reaches the boundary between the media. You may have to repeat this several times so that you can watch what happens at the boundary and in each medium.

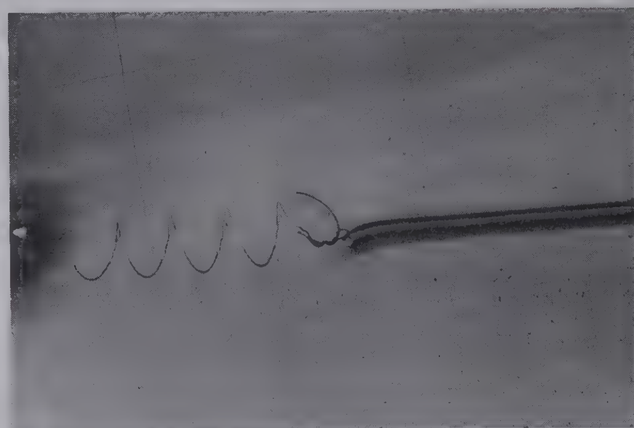


Figure 13.3

Q2 What happens to a pulse when it reaches a boundary between two different media?

Repeat now a second case with a pulse incident on the boundary from your partner's end.

Summarize your observations in a table like Table 13.1.

Table 13.1

	Pulses	Characteristic of Pulse				
		Shape (sketch)	Speed	Amplitude	Sign	Length
CASE 1	incident in medium 1					
	reflected in medium 1					
	transmitted in medium 2					
CASE 2	incident in medium 1					
	reflected in medium 2					
	transmitted in medium 1					

Q3 You have observed how a pulse behaves when the change in the medium is

(a) from the medium to a fixed end (your partner's hand),

(b) from one medium to a slower one,

(c) from one medium to a faster one.

What do you predict would happen if a pulse encountered a boundary between the medium and nothing at all (a free end)?

Additional Questions

Q4 If you measured the speed and length of the pulse accurately or if you have time to repeat the experiment, calcualte the ratio of: (a) the speeds v_1/v_2 (b) the pulse lengths ℓ_1/ℓ_2. Compare your results.

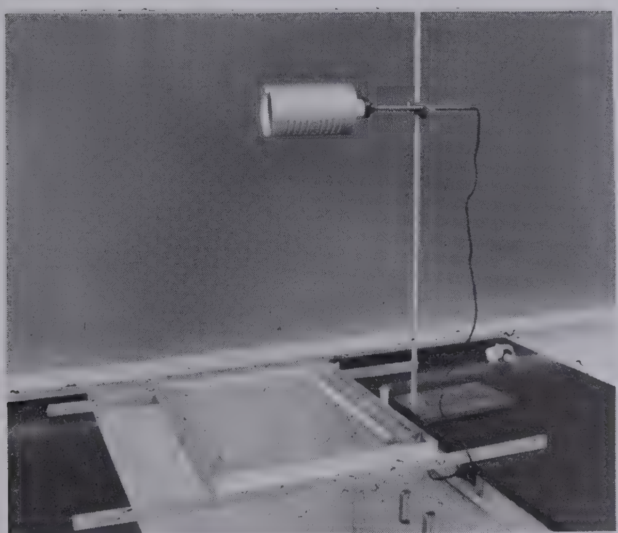
Q5 If you measured the amplitides carefully, using the fact that the *energy* $\propto$ *(amplitude)*^{2}, find the percentage of the incident pulse's energy reflected and transmitted in each case.

Experiment 13.3 Waves in a Ripple Tank — Propagation and Speed

On a coil spring or rope, you produced waves which travelled along a straight line in only one dimension. To get a more complete picture of wave behaviour, we can investigate waves travelling on the surface of water in a ripple tank. This surface forms a plane or two-dimensional surface.

Set up the ripple tank as shown below.

Figure 13.4



Light from the lamp, which acts as a point source, passes through the water and strikes the screen. A wave travelling on the surface of the water shapes it so that the crests and troughs act as lenses which concentrate the light on the screen as shown in Figure 13.5. The image on the screen is bright below crests and dark below troughs. Since the light spreads out from the source, the image is magnified.

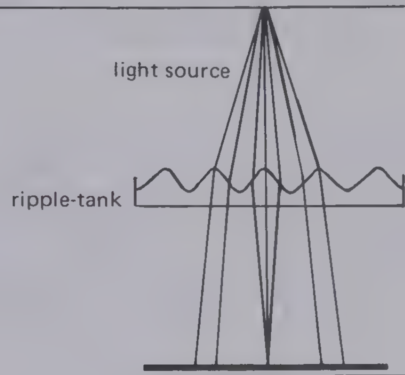


Figure 13.5

Fill the tank to a depth of approximately 1 cm of water. Level the tank so that the depth is the same at each corner. Place screen dampers around the tank's inside perimeter to reduce unwanted reflections.

SINGLE PULSES

Begin with single pulses from a point source. Touch the surface lightly with your finger tip near the centre of the tank. Watch the image of the circular pulse on the screen below. Repeat, making careful observations so that you can sketch what you see and answer the following questions.

Q1 How does the speed of the pulse in various directions compare? How can you tell from the shape of the pulse?

Next, generate single, *straight* pulses with a dowel or piece or broom handle. Place the dowel near one edge of the tank and roll the dowel about one-half centimetre. Watch the behaviour of the pulse as it moves down the tank.

Q2 Why does the pulse remain straight as it moves down the tank?

Using a stopwatch measure the speed of the pulse.

PERIODIC WAVES

To produce periodic straight waves, you can roll the dowel backward and forward with a constant frequency.

Now slow the frequency of the waves.

Q3 When the frequency is decreased, what happens to (a) the wavelength, (b) the speed of the waves?

Predict what would have happened to the wavelength and speed if a frequency greater than the first one had been used. Repeat the experiment to check your prediction.

If an electric wave generator is available, you can use it instead of rolling the dowel to produce periodic waves. It can be set up as shown in Figure 13.6.

Figure 13.6

Adjust the frequency of the generator to a value near the middle of its range and do the experiment as outlined above. If you have extra time you may want to make actual measurements of frequency, wavelength, and speed for the waves. This procedure follows.

MEASURING v, f, AND λ

Using a stroboscope, as shown by your teacher, observe the image of the waves on the screen. Adjust the frequency of the strobe at a constant speed and have your partner time 10 revolutions of the stroboscope with a stopwatch. (Do not worry if you were unable to keep the wave pattern perfectly stopped during this measurement. You may have turned a little too slowly or too quickly at various times but on the average you have the correct frequency.) Repeat the measurement. Use your results to calculate the frequency of the waves.

To find the wavelength of the waves, again "stop" the wave motion with the stroboscope and have your partner place two objects, such as pencils or rulers, a whole number of wavelengths apart on the screen. Then measure the distance between the markers and divide by the number of wavelengths observed between the markers to find the wavelength λ for the waves.

Using the universal wave equation, $v = f\lambda$, calculate the speed v of the waves. Compare with the value of the speed for a single pulse found earlier in the experiment.

Now, decrease the frequency of the generator and using the same techniques, measure f and λ. Use your results to calculate v. Repeat for a higher frequency. Tabulate your results.

Estimate the percentage uncertainty in your values for v.

Q4 Based on your results, how is the speed of a periodic wave affected by changes in frequency?

Q5 What effect does a change in frequency have on the wavelength of periodic waves? Why?

EFFECT OF DEPTH

If you have time, lower the depth of the water and find out how wave speed depends on the depth of water.

Additional Questions

Q6 As pointed out, the image of the waves is magnified. To what extent were the waves magnified in your experimental setup? Devise a method to measure the magnification factor.

Q7 Based on the magnification factor from Q5, what were the actual speeds and wavelengths for the waves in the experiment?

Experiment 13.4 Reflection of Waves

In experiment 13.2, you investigated reflection of one-dimensional waves hitting a boundary head-on. In this experiment, you will try to find out how waves in the ripple tank reflect from barriers of various shapes placed at different angles to the incident waves.

Set up the ripple tank as you did in Experiment 13.3 with a water depth of approximately 0.5 cm. Add a drop of liquid soap solution to improve the wetting of the water at each barrier in the tank.

To study reflection, it is advisable to use single incident pulses so you can use the dowel as before.

REFLECTIONS AT A PLANE BARRIER

Place a straight barrier across the tank in the path of the pulses. Align the dowel at the edge of the tank parallel to the barrier. Generate a single straight pulse toward the barrier. Watch the pulse as it hits and reflects from the barrier.

How do the pulse's characteristics before and after reflection compare?

Try generating straight pulses at various angles to the barrier. If you want to measure the angles of incidence and reflection for the pulses, do so by aligning rulers or other objects with the images of the pulses on the screen.

Draw a diagram to illustrate one of these cases of reflection.

Q2 Based on your results, what is the relationship between the directions of incident and reflected pulses?

Next, generate a circular pulse by dipping your finger in front of the barrier. Repeat several times. Draw a diagram to illustrate this reflection.

Q3 From where do the circular pulses reflected at the plane barrier appear to come? Show this point on your diagram.

REFLECTIONS AT A CURVED BARRIER

Place a piece of rubber tubing in the tank, bend and hold in place as shown in Figure 13.7. (This barrier should be approximately parabolic.)

Figure 13.7

With the dowel, generate straight pulses toward the concave side of the curved barrier. Observe various points along the wave front before and after it strikes the barrier. Repeat several times.

Draw a diagram to illustrate this reflection.

Q4 Where does the energy of the incident pulse go after reflection? What is this point called?

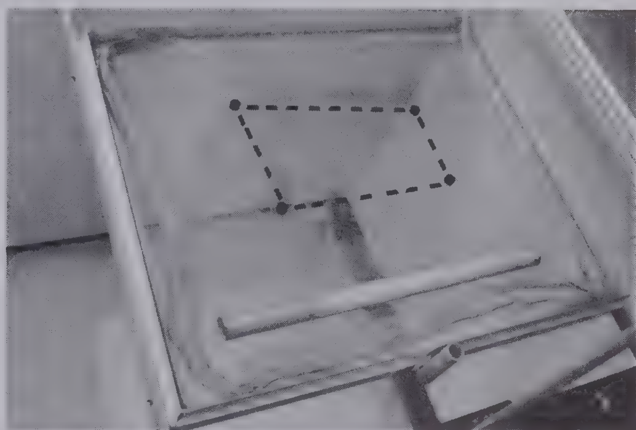
Q5 What happens if you dip your finger in still water at the point where the pulses converge?

Experiment 13.5 Refraction of Waves

In Experiment 13.3 you may have found that the speed of water waves is changed when the depth of the water changes. Consequently, you can set up two different depths in the ripple tank to represent two different media. Then, you can investigate the behaviour of two-dimensional waves as if they were passing from one medium into another.

Support a glass plate as shown in Figure 13.8 so that the top of the plate is level and approximately 1.5 cm above the bottom of the tank. Pour water into the tank until the glass plate is uniformly covered to a depth of not more than 0.2 cm.

Figure 13.8



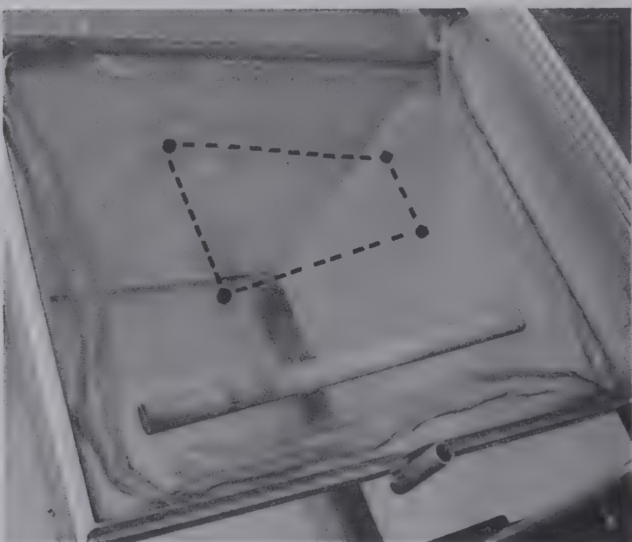
Predict what will happen to the waves as they pass from the deep to the shallow regions of the water. (Consider characteristics such as speed, wavelength, frequency, and direction.) Then, using low frequency plane waves, check your predictions. (If you want to make actual measurements of characteristics of the waves, use a stroboscope as you did in Experiment 13.3.)

Draw a diagram showing clearly what happened.

Q1 What should happen to the speed, wavelength, frequency, and direction of waves in a similar experiment where they passed from shallow to deep water?

Now, turn the glass plate so that the front edge is at an angle to the incident waves as shown in Figure 13.9.

Figure 13.9



Predict what will happen to the waves this time as they pass from deep to shallow water.

Using the same low frequency, study the behaviour of the waves crossing the boundary between the deep and shallow water and compare results with your prediction.

Q2 What happens to the direction of the waves?

Q3 How do the wavelengths, speeds, and frequencies in the deep and shallow regions compare?

Index of Refraction

If you wish to find a definite relation between the directions of the waves in the two media, you can measure the angles of incidence and refraction on the screen. (See the text page 93 to see how these angles are defined.) To do this, observe the waves through a stroboscope and have your partner align two pencils or rulers with the incident and refracted wave fronts of the "stopped" pattern. Keep the frequency constant and turn the plate to three or four different angles of incidence. Measure the angles of incidence and refraction in each case and tabulate your data.

Plot a graph of angle of refraction versus angle of incidence.

Q4 Based on your data, is there a simple relation between the angle of refraction and the angle of incidence? How do your results compare with Snell's Law,

$$\frac{\sin \angle i}{\sin \angle r} = a\ constant?$$

Q5 What is the index of refraction for your setup?

Additional Questions

Q6 How do the relative depths of the shallow and deep regions of the tank affect the amount of refraction? Investigate this question by using various depths of water in the tank and above the glass plate.

Q7 How are the ratios $v_{deep}/v_{shallow}$ and $\lambda_{deep}/\lambda_{shallow}$ related to the index of refraction in the tank? Make measurements in the tank to answer this question.

Q8 Is the index of refraction for your setup the same for all frequencies? Vary the frequency of the generator and make measurements to answer this question.

Experiment 13.6 Waves at Corners and Slits

You have seen in previous experiments how the direction of segments of a wave front can be changed by reflection and refraction. Is there another means by which the direction of waves can be changed?

Cut a small piece of paraffin with sharp corners and place it in the tank about 10 cm from the generator as shown in Figure 13.10.

Figure 13.10

Generate long wavelength periodic waves and watch as they travel along the tank and by each corner of the block. You may use a stroboscope to "freeze" the waves.

Draw a diagram showing several wave fronts in front of and behind the block.

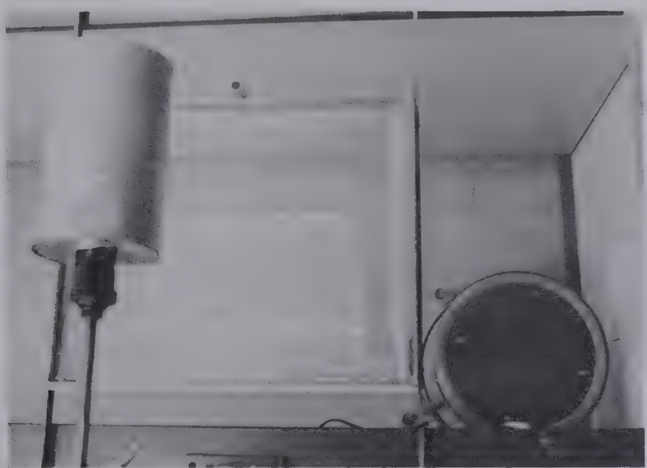
Q1 Is a "shadow" (undisturbed region) created behind the block? How do you know?
Q2 After passing the block, are the wave fronts straight on either side of the block? Why?

Slowly increase the frequency of the waves and note any changes in the pattern.

Q3 How is the amount of bending at each corner affected by decreasing the wavelength?

Another arrangement which shows a similar effect is shown in Figure 13.11. Set up the tank in this way and generate long wavelength waves toward the slit. Investigate the situation until you are able to answer the following questions.

Figure 13.11



Q4 What happens to the direction of propagation of various segments of a wave front as it passes through the slit? Illustrate your answer with a diagram.
Q5 What effect does changing the wavelength have on the pattern?
Q6 What effect does changing the slit width have on the pattern?
Q7 Under what circumstances are waves affected the least when passing through the opening?

Additional Question

Q8 Using Huygen's principle (page 96 in the text), how would you account for your observations in this experiment?

Experiment 13.7 Interference of Waves

In previous experiments you investigated what happens when waves encounter objects or changes in medium. Here we will investigate what happens when one wave meets another wave in the same medium. You will look at waves in a coil spring first and then, in Experiment 13.8, look for analogous behaviour in a ripple tank.

SUPERPOSITION IN A COIL

Obtain one of the coil springs used in earlier experiments and with your partner, stretch it out on a smooth, level floor. Now send two similar, *single* pulses (same amplitude and same sign) from each end of the coil.

Repeat and describe what happens when the pulses meet.

Then send one positive and one negative pulse from opposite ends and describe what happens when these pulses meet.

Q1 Do the pulses reflect off each other or pass through each other when they meet? How can you be sure?
Q2 How does the amplitude of the coil for the combined pulses compare with the amplitudes of the two separate pulses when (a) they both have the same sign, (b) they have opposite signs?
Q3 Based on your results, what do you predict would happen if the amplitudes of the two meeting pulses were related as shown in Figure 13.12(a), (b), (c)?

Test your predictions using the apparatus.

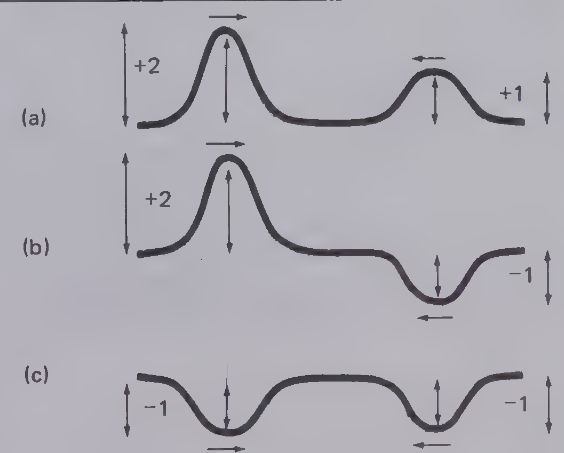


Figure 13.12

STANDING WAVES ON A COIL

What happens if two *periodic* waves travel toward and through one another? To find out, generate periodic waves in phase with the same frequency at each end of the coil.

Q4 Are all points along the coil vibrating through the same cycle? Explain your answer.
Q5 Why is this pattern produced called a *standing wave?*

Enlist a bystander to mark the points along the coil which are not moving. These points of zero or no displacement are called *nodes.*

Q6 How far apart are the nodes (a) in metres, (b) in terms of λ?
Q7 How do particules mid-way between nodes behave? (Why are these points called *antinodes*?)

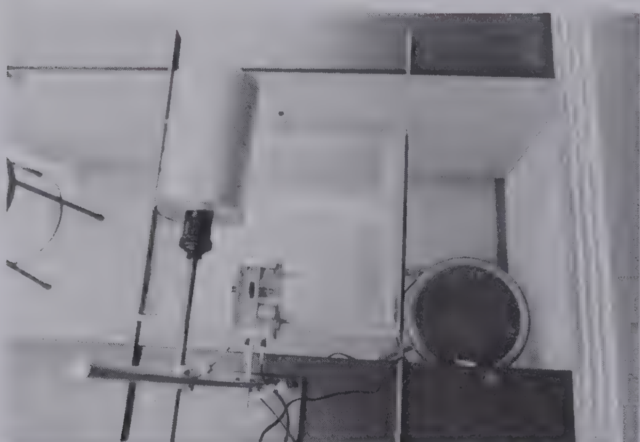
Experiment 13.8 Interference in the Ripple Tank

The principle of superposition which you investigated in a one-dimensional medium in Experiment 13.7 should also apply to the ripple tank. Here you will experiment with two-dimensional plane and circular waves to see how they interact.

Set up the ripple tank as before to a 1.0 cm depth.

To begin, place a straight barrier halfway across the tank as shown in Figure 13.13.

Figure 13.13



To generate periodic plane waves toward the barrier, use the dowel or an electric rippler. Watch the waves on the screen and draw a diagram showing the pattern between the generator and barrier and in the region where the waves travel by the barrier.

Q1 How does the behaviour of the waves in the two regions in your diagram compare? Explain the effects in terms of properties of waves.
Q2 How does the distance between nodes in the standing wave compare with the wavelength of the the travelling wave?

Now, remove the generator and barrier and dip two finger tips side by side about 5 cm apart near one end of the tank. Watch as the two circular pulses overlap and describe the behaviour. To produce periodic circular waves, dip your finger tips in unison at a constant frequency or use an electric generator equipped with two-point sources. Look for nodal points in the pattern. On the screen these will appear as grey regions contrasting with the bright and dark regions which correspond to crests and troughs. Investigate the phenomenon so that you can illustrate it with a diagram and answer the following questions.

Q3 How does the wave pattern between the point sources compare with the standing waves on the coil spring in Experiment 13.7?
Q4 Starting from the nodes between the point sources, your sould see lines of nodes radiating out into the tank. What is the shape of these nodal lines?
Q5 What causes the nodal lines?
Q6 What is happening in the regions between the nodal lines? Why?
Q7 As the frequency of the sources increases, what happens to the pattern of nodal lines?
Q8 What effect does changing the spacing between the sources have on the pattern of nodal lines?

Similar patterns can be produced with overlapping concentric circles as shown in Activity 13.5. These may help you to understand this phenomenon.

Additional Questions

Q9 How is the number of nodal lines related to the ratio of the spacing of the sources to the wavelength λ of the waves (d/λ)?
Q10 In the text, page 101, a relation between λ and d, ℓ and x, three parameters which are shown in Figure 13.14, is derived. P is a point on the first antinodal line.
How can you use the relation $\frac{\lambda}{d} = \frac{x}{\ell}$ to find the wavelength for waves from the sources S_1 and S_2? Try it.

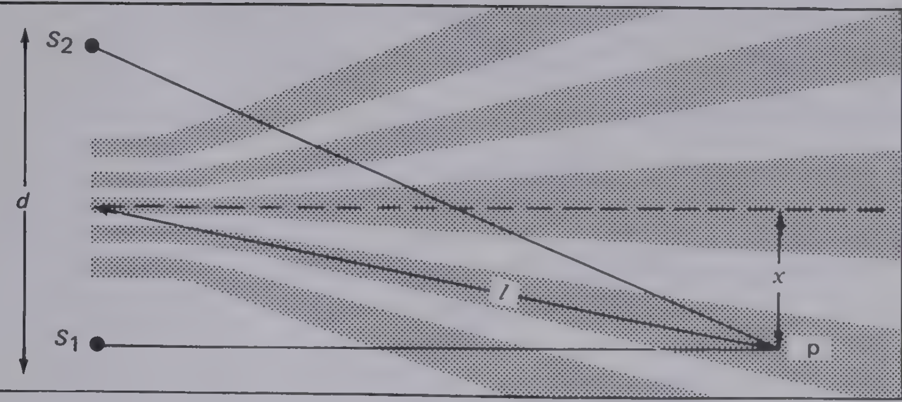
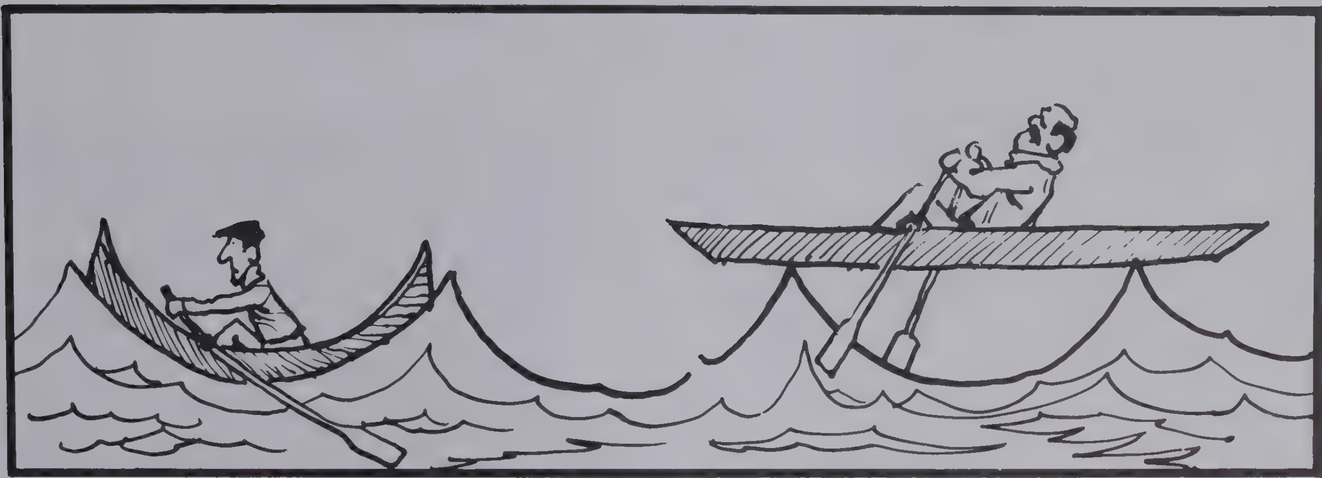


Figure 13.14

Activities

An ocean traveller has even more vividly the impression that the ocean is made of waves than that it is made of water.

Sir Arthur Eddington (1882-1944)



Activity 13.1 Polarization of Waves

If there is a rotator in your laboratory, set it up so as to produce waves in a piece of rubber tubing as shown in Figure 13.15. Cut slots in two pieces of stiff cardboard. Place one card with the slot vertical, near the rotator, to polarize the waves (the polarizer). Hold the other card (the analyser) about the same distance from the fixed end of the tubing. Rotate the analyser slowly around the axis of the wave, stopping when the slot is oriented at various angles relative to the slot in the polarizer (try relative angles of 0°, 90°, 45° etc.). Describe the wave on the tubing in the regions between (a) the rotator and polarizer, (b) the polarizer and analyzer, and (c) the analyser and the fixed end.

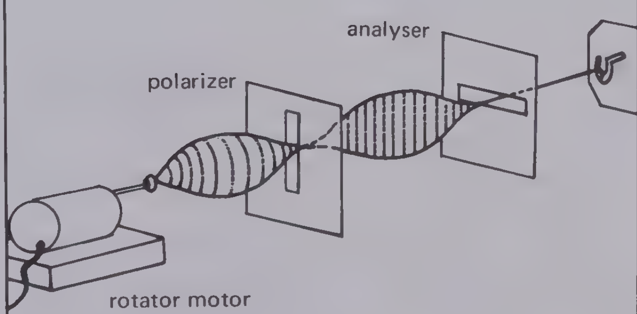


Figure 13.15

Relate your observations to the discussion of polarization on page 82 of the text.

Activity 13.2 Vibrations of a Tuning Fork

A tuning fork produces sound waves by vibrating air molecules. To find out just how the tines of the fork move, you can use an electronic stroboscope. (The fork moves so quickly that you cannot see it with the unaided eye.) Start a fork vibrating and illuminate it with the stroboscope. Adjust the frequency of the strobe until the motion appears to slow down enough so that you can analyse just what is happening. Also, you can study vibrations of guitar or piano strings using the strobe in the same way.

Based on your observations, explain how the fork produces a sound wave in air.

Activity 13.3 Solar Oven

One approach to solving the energy crisis is to find ways of using energy from the sun directly. The solar oven is a device which is being developed to achieve this purpose. Find out how solar ovens are designed.

If you have time, and some materials, make your own model of a solar oven. If you can make it work, test it with a small piece of steak. Compare results with a conventional barbecue.

Activity 13.4 Thought Problem

When you have observed and understood waves in one dimension and then extended to two dimensions, it is useful to take the next step. This would mean thinking about waves travelling in space which has three dimensions.

Q1 What would be the shape of a wave from the point source in space? How would it change as it moved outward from the source?
Q2 How would a wave in space reflect when it hit a flat wall?
Q3 What would happen if the wave tried to pass through a small hole in a large flat surface?
Q4 What kind of interference pattern would be produced by two waves from point sources overlapping in space? (Example: Sound from stereo speakers.)

Q5 In an ideal one-dimensional medium, the energy in a pulse (shown by its amplitude) remains constant. In a two-dimensional medium, the pulse's energy is spread out over a larger and larger circle. What happens to the energy of a pulse in space?

Activity 13.5 Moiré Patterns

Obtain two clear sheets of overhead projector acetate. On one, carefully draw with a felt pen a series of concentric circles as shown in Figure 13.16 representing a periodic wave from a point source. (Use approximately 2 or 3 mm so that the spaces are about as wide as the lines. Repeat on the other piece of acetate. Then superimpose these sheets on an overhead and project their image onto a screen. Slowly move the sheets and look for the appearance of a pattern. You can obtain a similar effect by photographing Figure 13.16 and superimposing two negatives or transparent slides.

Figure 13.16

Try other types of overlays such as parallel straight lines equally spaced at about 3 mm or parallel lines whose spacing changes systematically. Describe the moiré pattern in each case.

You can also see moiré patterns with pieces of cheesecloth or wire mesh or even in crossed snow fences. A good reference which shows many uses of these patterns is the article Moiré Patterns in the May 1963 issue of *Scientific American*, also available as offprint 299.

Activity 13.6 Wave Machine

A wave machine is a useful tool in studying properties of waves. One version is made from a metre-long piece of rubber tubing, shown in Figure 13.17. Puncture the tubing at equally spaced intervals (say every 2 cm). Through each hole push a straight piece of heavy wire (a welding rod will do nicely). If their lengths and weights are all the same, you will have a continuous one-dimensional medium. Generate pulse from the free end and investigate propagation, reflection, and standing waves. By using wires of two different lengths or weights for top and bottom halves of the tubing, you can represent two different media and investigate reflection and transmission of waves across the boundary between them.

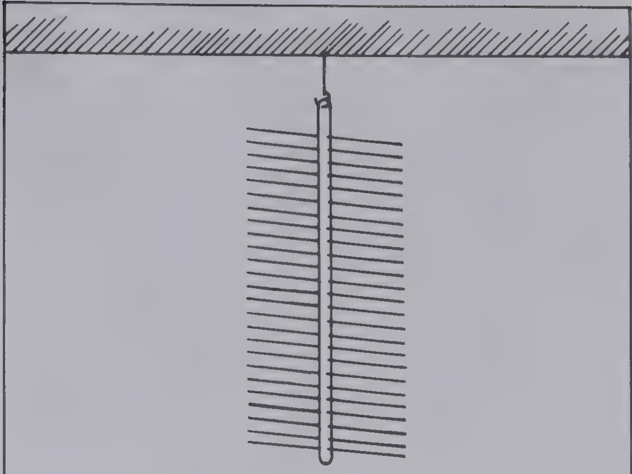


Figure 13.17

Film Loop Notes

There are several excellent film loops on waves. If some of them are available you may want to use them to supplement the experiments; or you could review this section by viewing the loops.

Some can be used for direct measurement. For example, if one frame of a loop on refraction in the ripple tank is stopped and projected on the chalkboard, you can measure the angles of incidence and refraction and wavelengths on both sides of the boundary between the deep and shallow regions. You may use the same technique in several frames.

View loops which are available and, with your teacher's assistance, proceed in the way which will be most useful for you with each loop.

Answers to End-of-Section Questions

Chapter 10

Q1 No. The law only specifies that mass is conserved, not volume.

Q2 a) Since the dust originates from outside the earth, the earth alone is not a closed system.

b) At least as large as the solar system.

c) The amount of meteoric dust is only $\frac{9 \times 10^{6}}{6 \times 10^{24}} \times 100 = 1.5 \times 10^{-16}\%$ of the total mass of the earth. For practical purposes, it seems reasonable to consider the earth as a closed system.

Q3 a) Yes.

b) The gravitational forces on the pucks are *balanced* by the force of the table upon the pucks.

c) Forces acting on the earth are not relevant in deciding whether or not the pucks and the spring form an isolated system. Only forces acting on the pucks and spring need be considered for this.

Q4 It was the only quantity that remained the same before and after the collision. That is, it was conserved.

Q5 a), c), and d).

Q6 a) 4.2 kg m/s toward home plate

b) 15,000 kg m/s east

c) 45,000 kg m/s north

Q7 a) 8 m/s right

b) 0.5 m/s right

Q8 5.3 m/s in the initial direction of the bullet.

Q9 $\frac{m_A}{m_B} = \frac{3}{2}$

Q10 i) Highly elastic a), c), f)

inelastic e)

Completely inelastic b), d)

ii) In all cases.

iii) Kinetic energy is not conserved 100% in any of the collisions, but it would be conserved to probably better than 80% in a), c), and f).

Q11

	$\vec{p}$	KE
a)	6 kg m/s right	9 kg $\frac{m^2}{s^2}$
b)	6 kg m/s left	9 kg $\frac{m^2}{s^2}$
c)	12 kg m/s right	36 kg $\frac{m^2}{s^2}$
d)	12 kg m/s left	18 kg $\frac{m^2}{s^2}$

Chapter 11

Q1 1 joule is the work done when a force of 1 newton moves a body a distance of 1 metre.

Q2 When the body does not move, or when the body does not move in the direction of the force.

Q3 a) 15 joules

b) 22.5 joules

c) 2×10^5 joules

d) 6 joules

e) zero

Q4 10 N

Q5 30 watts

Q6 2000 watts (2 kw)

Q7 10 seconds

Q8 2.4×10^5 joules

Q9 a) 180 joules

b) 1.1×10^5 joules

c) 6.8×10^5 joules

Q10 2 m/s

Q11 $N - m = (kg\frac{m}{s^2})\ m$

Q12 Discussion

Q13 Stretch it or compress it. In either case, you do work on the spring and this work is stored as "spring potential energy".

Q14 e)

Q15 Discussion

Q16 Work is done by the person in lifting the body against the gravitational force. This work does not increase the speed of the body, but only changes its position. The work goes into gravitational potential energy.

Q17 About 1 joule.

Q18 2 metres

Q19 The gravitational potential energy of a body at any one position is equal to the work done in moving from *any* reference level to that position. This amount can have various values depending on the choice of reference level.

Q20 e) only

Q21 Discussion

Q22 Discussion

Q23 Discussion

Q24 Discussion

Q25 Heat was supposed to occupy bodies in the form of a fluid called "caloric".

Q26 Discussion

Q27 a) Only about $7 \times 10^{-8}\%$ is received as useful energy at the surface. The rest is radiated into space.

b) about 66%!

c) About 40 yrs! This figure is based on proven fossil reserves only and is an average figure. The figure for coal alone is much higher—about 1200 years. Nevertheless, the implication from this figure is startling. The whole history of civilizations driven by fossil fuels may well turn out to be shorter than the duration of the Old and Middle Kingdoms of Europe, or of the Byzantine Empire.

Q28 Discussion

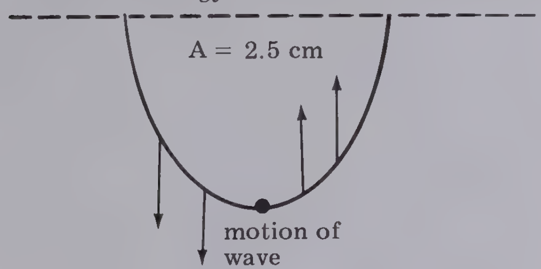
Q29 Discussion

Chapter 12

Q1 4.2 m from fulcrum
Q2 a) 12
b) 4.2 cm
c) 12 cm (at least)
Q3 120 N
Q4 1500 N
Q5 1/5
Q6 a) MA = 5
b) 10^3N
c) 1.5×10^4 joules
d) 15 m
Q7 a) 500 N
b) 4000 joules
c) 4
Q8 300 N
Q9 The force applied is less than if the object were lifted directly.
Q10 30 N approximately, 1000
Q11 Discussion
Q12 Discussion
Q13 Discussion
Q14 Discussion
Q15 Discussion
Q16 Discussion
Q17 Discussion
Q18 Discussion

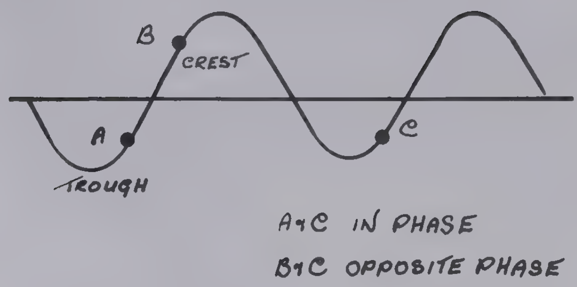
Chapter 13

Q1 A wave is a phenomenon by which energy propagates through distances as a result of vibratory motions.
Q2 A transverse wave is a wave in which the particles of the medium vibrate at right angles to the direction of energy transfer.
Q3

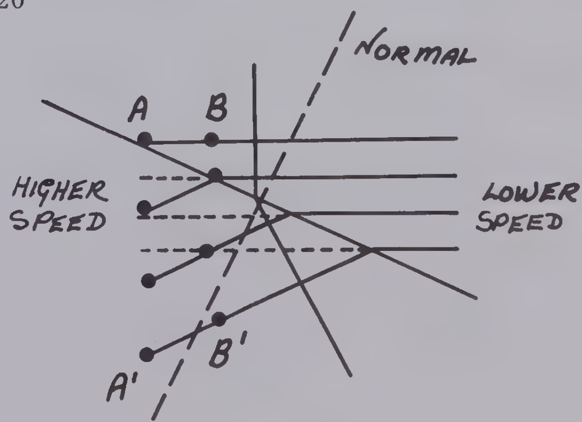


Q4 Energy is transferred into heat energy in the wave medium and surrounding medium.
Q5 a) A longitudinal wave is a wave in which the particles of the medium vibrate parallel to the direction of energy transfer.
b) A compression is a region of greater than normal density of a medium.
c) A rarefaction is a region of lower than normal density of a medium.
Q6 a) Frequency of a periodic vibration is the number of complete vibrations per unit of time.
b) The period of a vibration motion is the time taken for one complete vibration.
Q7 One hertz is a frequency of one cycle per second.

Q8 a) $f = 2$ Hz
b) $T = \frac{1}{2}$ second
Q9



Q10 Period of wave = 2 s — This is the time required for the wave to travel one wavelength.
Frequency of wave = $\frac{1}{2}$ Hz — This is the number of complete cycles of any point in the medium. (per second)
Q11 Move a rope to and fro in many different planes—all of which are at 90° to the length of the rope itself.
Q12 Discussion
Q13 $\lambda = 3.0$ cm
Q14 Discussion
Q15 It is based on a kinematics relationship and the definitions of wavelength, period, and frequency which hold true for any kind of wave. The universal wave equation is essentially just the definition of speed expressed in wave terminology.
Q16 a) $\lambda = 5.0$ cm
b) i) speed remains unchanged
ii) wavelength is halved, to 2.5 cm
Q17 A wave ray is a line which represents the direction of propagation of any one point along a wave front. It is always perpendicular to the wave front.
Q18 15 cm/s
Q19 The angle of incidence is equal to the angle of reflection
Q20



Q21 a) Waves travelling at an oblique angle into a medium where wave speed is decreased.

b) Waves travelling at an oblique angle into a medium where wave speed is increased.

Q22 $n_{12} = 1.41$

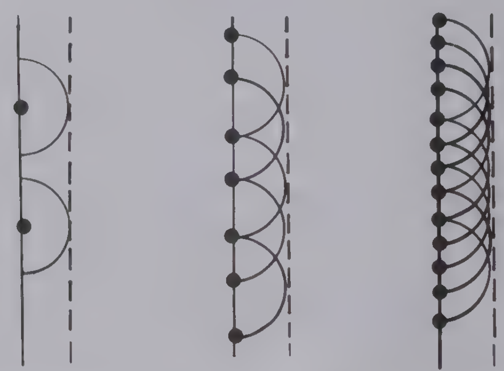
Q23 $n_{12} = 1.50$

$\angle R = 25.4°$

Q24 Every point on a wave front may be considered to behave as a point source for new waves generated in the direction of the waves propagation.

Q25 See diagram

Q26



EACH POINT ON THE WAVE FRONT CREATES A DISTURBANCE WHICH MOVES JUST AS FAR FORWARD. THE SHAPE IS PRESERVED.

Q27 5 cm

Q28 When two or more waves meet at a point in a medium, the actual displacement of the medium is the sum of the displacements of each wave alone.

Q29 Discussion

Q30 A node is a place of continuous zero amplitude of displacement of a medium.

Q31 Discussion

Q32 Discussion

Q33 PS_1 is very nearly parallel to PS_2.

Q34 Discussion

Chapter 10

10.1 A system of bodies on which no net force acts from outside the system.
10.2 Discussion
10.3 In any isolated system the total momentum before an interaction is equal to the total momentum after the interaction.
10.4 Primarily because it is a conserved quantity.
10.5 $\vec{p}_{bear} = 750 \text{ kg}\frac{m}{s}$ north
$\vec{p}_{bullet} = 7 \text{ kg}\frac{m}{s}$ south
No. For this to happen, the momenta would have to be of equal magnitudes but of opposite directions. Then
$\vec{p}_{\text{total before}} = 0 = \vec{p}_{\text{total after}}$
10.6 $\vec{v}_{gun} = 2\frac{m}{s}$ in opposite direction to shell.
10.7 $7.5 \times 10^{-14}\frac{m}{s}$ (assumes average mass per person = 50 kg).
10.8 It is transferred to the molecules of the air and of the table.
10.9 $1\frac{m}{s}$ in original direction.
10.10 $1.7\frac{m}{s}$ in original direction.
10.11 9.0 kg
10.12 $0.07\frac{m}{s}$ left.
10.13 Discussion
10.14 Discussion
10.15 The rubber ball transfers twice as much momentum to the wall.
10.16 Discussion
10.17 Discussion
10.18 Discussion
10.19 Discussion
10.20 Discussion
10.21 Discussion
10.22 Discussion
10.23

Problem 9	KE_{before}	$= 4.5 \times 10^9$ units
	KE_{after}	$= 1.5 \times 10^9$ units
Problem 10	KE_{before}	$= 11$ units
	KE_{after}	$= 10.3$ units
Problem 11	KE_{before}	$= 12.5$ units
	KE_{after}	$= 12.5$ units
Problem 12	KE_{before}	$= .052$ units
	KE_{after}	$= .0098$ units

10.24 a) about $100\frac{m}{s}$
b) about $4.6 \text{ kg}\frac{m}{s}$
c) less than 0.003 s
d) at least 1.5×10^3 N
10.25 Discussion
10.26 $\vec{v}_1' = \frac{m_1 - m_2}{m_1 + m_2}\vec{v}_1$

$\vec{v}_2' = \frac{2m_1}{m_1 + m_2}\vec{v}_1$

Chapter 11

11.1 40 joules
11.2 a) 261 kw
b) 261 kw-hr or 9.43×10^8 joules
11.3 a) 5 seconds
b) 2.5 seconds
11.4 a) i) 15 joules ii) 15 joules
b) i) 7.5 watts ii) 3.75 watts
11.5 a) 1.14×10^{-19} joules
b) 8.8×10^{18} electrons
11.6 Discussion
11.7 a) $a = 0.5 \text{ m/s}^2$
$t = 12$ seconds
$v = 6$ m/s
b) $v = 6$ m/s
c) Discussion
11.8 Chemical potential energy is essentially electrical potential energy arising from the spacing of molecules and the positions of electrons and protons within those molecules.
11.9 a) 6000 joules
b) 1000 joules
c) The gravitational potential energy of the bag with respect to any given reference level is equal to the work required to lift the bag from the reference level to its position.
11.10 a) 3.25×10^{11} joules
b) 5.4×10^9 watts
11.11 4 m/s
11.12 a) 60 joules
b) 60 joules
c) 78 m/s
11.13 a) 25 joules
b) 10 m/s
c) Discussion
d) Discussion
11.14 His speed at the bottom depends only on the height of the slide.
KE at bottom = *PE* at top
$\therefore \frac{1}{2}mv^2_{(bottom)} = mgh_{(top)}$
and $v = \sqrt{2gh}$
11.15 a) 6 joules
b) 26 joules
c) Discussion
11.16 a) 20 metres
b) 150 joules
11.17 a) Ball A will go twice as high as ball B
b) Ball C will go four times as high as ball D.
11.18 a) Graphs
b) $\frac{\text{distance required from 60 km/hr}}{\text{distance required from 30 km/hr}} = \frac{4}{1}$
$\frac{\text{d (from 90 km/hr)}}{\text{d (from 30 km/hr)}} = \frac{9}{1}$
c) $\frac{\text{time required from 60 km/hr}}{\text{time required from 30 km/hr}} = \frac{2}{1}$
$\frac{\text{t (from 90 km/hr)}}{\text{t (from 30 km/hr)}} = \frac{3}{1}$

11.19 Discussion
11.20 Discussion
11.21 Discussion
11.22 a) 1000N
b) 1500 joules
c) 500N
d) i) 2100 joules
ii) 1500 joules
iii) The remaining 600 joules would be converted into heat.

IYSICS: A HUMAN ENDEAVOUR

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e Nature of Light and Sound
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e New Physics

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